Volume 2 AUGUST, 1932 Number 2

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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The JOURNAL OF SEDIMENTARY PETROLOGY is published by the Society of Economic Paleontologists and Mineralogists, a division of The American Association of Petroleum Geologists. Numbers are issued in April, August and December.

The subscription price of the JOURNAL OF SEDIMENTARY PETROLOGY is $3.00 per year prepaid to addresses in the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Dominican Republic, El Salvador, Bolivia, Colombia, Honduras, Nicaragua, Peru, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands.

Single numbers, $1.50 each.

Postage is charged extra: For Canada, 20 cents on annual subscriptions (total $3.20), and for all other countries in the Postal Union, 40 cents on annual subscriptions (total $3.40).

Claims for non-receipt of preceding numbers of the JOURNAL must be sent to the secretary-treasurer within three months of the date of publication in order to be filled gratis.

The JOURNAL will furnish reprints at cost. Orders should accompany corrected galley proof.

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GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

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AUGUST, 1932

A CALCAREOUS BEACH ON THE COAST OF MAINE

PERCY E. RAYMOND AND H. C. STETSON
Harvard University, Cambridge, Massachusetts

Beach deposits made up in large part or wholly of fragments of shells or other calcareous particles are exceedingly common on the shores of tropical or subtropical seas, but almost unknown in north-temperate regions. It is true that windrows of shells collect near high-tide level at many places, but the beach in such cases is predominantly siliceous sand, so much so, in fact, that one often wonders what has become of the shells which have been broken up. To mention but one local example, if one visits Lynn beach, a few miles north of Boston, after a stormy day in winter, one finds it covered with shells. Yet an analysis of the sand reveals but the smallest percentage of calcium carbonate. At almost any time of year one can find concentrations of tiny fragments of shells in troughs of ripples on this beach, but even this material is not rich in calcium. A sample, scraped from the surface with the idea of getting as much shell as possible, was found to contain only 2.5 per cent $CaCO_3$.

The senior writer, having encountered a most remarkable shell beach at John o'Groat's, on the north coast of Scotland this last summer, became interested in these northern occurrences. (See *This Journal*, Aug. 1932). It so happened that the junior author had long been familiar with a somewhat similar strand on Little Cranberry Island, south of Mt. Desert Island, Maine. We accordingly spent two days in making a preliminary survey of it with the hope, which we think has been realized, that it would throw light on the origin of the Scottish example.

This may seem a trivial subject for study, but as a matter of fact it is bound up with the question of the origin of limestone in general, and of Paleozoic limestone in high latitudes in particular. Since limestone is at the present day accumulating chiefly in tropical and subtropical regions, we have rather tended to the conclusion that warm water is necessary for its formation.

THE BEACH ON LITTLE CRANBERRY ISLAND

The southwest point of Little Cranberry is formed of a small rocky islet tied to the main island by a double tombolo, with a small pond in a swamp between the beaches. The outer of these, which faces southeast towards the open Gulf of Maine, is a high barrier composed of pebbles and cobbles,

whereas the inner one, facing west toward Cranberry Harbor, is low and is composed largely of shell-sand (fig. 1). On a part of the coast where sand of any sort is rare, this beach has considerable local importance and has been used for years as a place for the beaching and repairing of vessels and small craft.

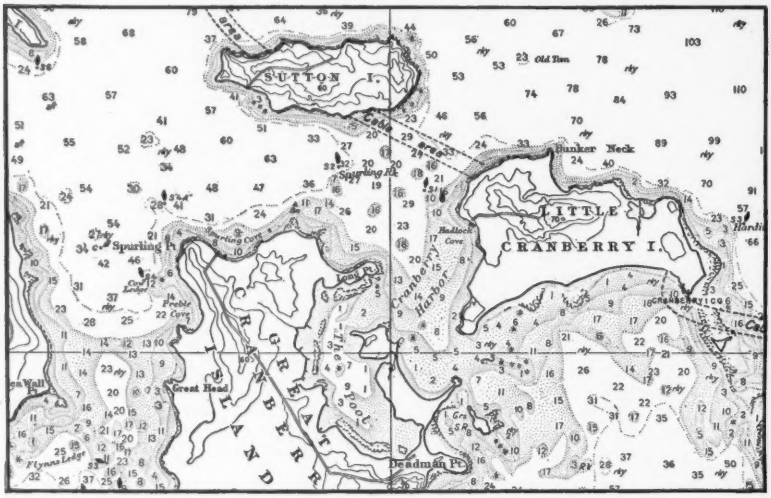

FIG. 1. The surroundings at Little Cranberry Island.*

* A part of sheet No. 306, U. S. Coast and Geodetic Survey, showing the surroundings of Little Cranberry Island, the Harbor, and the "Gut" and its seaward shoals. The surroundings are in feet at mean low water and the scale about 1¼ inches to the nautical mile.

The beach extends for about 800 yards from a small rocky headland south of Hadlock Cove to the point which forms the southwestern end of the island. Throughout its length, its surface shows a very much larger proportion of shell-sand than is commonly found on the beaches of New England. Digging shows that this is not a surficial phenomenon, but that the whole mass contains fragments of shells.

At both northern and southern ends of the beach, near the rocks, the material on the surface is coarse, containing many pebbles up to an inch in diameter, broken shells, and even entire ones recently cast up. Sand from just below high-tide level near the south end of the beach proves to be not only coarse but very poorly sorted, for 79 per cent of it has a diameter greater than 1 mm. The grade most abundant is that between 2.36 mm. and 1 mm. of which there is 34 per cent, whereas only 0.2 per cent is less than 0.125 mm.

A sample taken at half-tide about 150 yards south of the northern end

of the beach is coarse, but well sorted. Fifty-one per cent is in the grade between 1 mm. and one-half mm., nearly 47 per cent is above 1 mm. in diameter, and only 0.1 per cent is less than 0.125 mm. This material contains the highest concentration of shell fragments of any of the samples taken on shore, for it is 67 per cent $CaCO_3$.

Some parts of the beach are covered with cobbles, which, however, form only a surficial deposit, the shell-sand occupying spaces between and under them. Another part is actually bouldery, but near it is the least pebbly part of the whole beach. A sample taken in this most sandy area, just above low-tide level, shows good sorting, and much finer grain than the material nearer the ends of the beach. Forty-seven per cent of this material is in the grade between 0.50 mm. and 0.25 mm. A little less than 4 per cent has larger diameters than 1 mm., but only 0.3 per cent is smaller than 0.125 mm. In this sample the $CaCO_3$ amounts to 26.5 per cent, which is probably considerably lower than the average for the beach.

The top of the wide beach ridge, which is now grassed over, is four or five feet above ordinary high tide. The sand in this deposit is coarse and contains a high percentage of shell fragments. A sample taken about 150 yards from the north end of the beach contains 45 per cent of material greater than 1 mm. in diameter and less than 0.2 per cent less than 0.125 mm. Forty-nine per cent is between 1 mm. and 0.5 mm. Practically all the fine-grained material has been eliminated. Another sample, from the same deposit about 200 yards north of the south end of the beach is of much finer grain, only 8 per cent being above 1 mm. in diameter, 47 per cent is between 1 mm. and 0.5 mm., whereas nothing passed through the apertures of 0.125 mm. In both localities the greatest amount in any one grade is between 1 mm. and 0.5 mm., being nearly half in each case. The sample from the northern locality contains 58 per cent of $CaCO_3$.

This material above high tide shows faintly a stratification without very pronounced parting planes, the layers being two or three inches thick. A sample taken 18 inches below the surface contains 60 per cent $CaCO_3$. Its mechanical analysis is very much like that of the last sample described, although a little finer in grain, 57 per cent being in the grade between 1 mm. and 0.5 mm. in diameter.

CHIEF CONTRIBUTORS TO THE BEACH

Some attempt was made to determine the sort of animals whose skeletons contributed most to the calcareous part of the beach. A large sample, taken near the rocks at the north end of the beach, was passed through sieves of 4.699 mm. and 3.327 mm. apertures. On the former were caught 53 pieces of *Mytilus,* 49 of *Balanus,* 40 of undetermined pelecypods other than *Mytilus* and *Mya,* 10 of *Littorina,* 23 of other gastropods, 6 of *Mya,* and 1 of *Strongylocentrotus.* On the second sieve were 254 fragments of *Balanus,* 43 of *Mytilus,* 73 of other pelecypods, 9 of *Littorina,* 13 of other gastropods, and a small sand dollar. These fragments were weighed, with the following results: *Balanus,*

14.3 gr., *Mytilus,* 9.38 gr., pelecypods other than *Mytilus,* 11.69 gr., *Littorina,* 3.31 gr., other gastropods, 5.8 gr. and the sand dollar, 0.15 gr. Evidently at this end of the beach, pelecypods contribute most in weight, although fragments of barnacles are very much more numerous and therefore a more important constituent in the smaller grades. Gastropods are also important, echinoderms almost negligible.

At the southern end, a count of the fragments which passed through 4.699 mm. and were caught on 2.362 mm. showed the presence of 78 pieces of *Balanus* (1.93 gr.), 78 of *Mytilus* (1.82 gr.), 49 other pieces of pelecypods (1.11 gr.), probably including some *Mytilus,* 9 of gastropods (0.39 gr.) and 5 plates of *Strongylocentrotus* (0.11 gr.). As at the north end, pelecypods rank first and *Balanus* second as contributors to the coarse material.

In the finer grades identification of material becomes much more difficult, and the relative abundance was judged only by inspection. Fragments of *Balanus* have markings and conspicuous canals which help in their recognition. *Mytilus,* with which is included any fragments of the much more rare *Modiola,* is generally recognizable by its periostracum, its color, or in the smaller grades, from 0.25 mm. downward in the scale, by the way the shell breaks down into long prismatic fibres of asbestos-like appearance. In all grades of all samples fragments of barnacles and mussels are common. In the grades below 2.362 mm. spines of *Strongylocentrotus* are abundant in most samples. This is not surprising, for this sea urchin is extremely common in the water all about the island and many tests are seen in the windrows. Apparently the plates break up very readily, for only rarely is one found in the samples examined.

The conspicuous inorganic material in the beach consists chiefly of subangular, partially rounded fragments of the rocks of the general region. In the grades below 1 mm. in diameter, angular fragments of quartz and feldspar are common, becoming very abundant in the smaller grades. In sizes less than 0.25 mm. dark minerals and flakes of mica are abundant.

THE SOURCE OF THE SHELL FRAGMENTS

The two most important contributors to the shell-sand, *Balanus* and *Mytilus,* live most commonly on ledges or stony bottoms in the intertidal zone or just below it. The rocks at the northern end of the beach support many barnacles, and the great abundance of their fragments in the sand south of these rocks suggests a local origin. Colonies of *Mytilus* are found near and just below low-tide level all along the beach, and also on the ledges at the southern point. *Littorina* is common on the rocks at the north end of the beach. With *Tectura* it probably supplies most of the fragments of gastropods. Most of the other mollusca, except for an occasional piece of *Mya,* are too fragmentary for determination.

The animals living in the vicinity of the beach are apparently of the same sorts as those whose shells make up a large part of it, but the local source of supply is not great enough to account for more shells than would be found

on the ordinary sand beach north of Cape Cod. The accumulations must be due to the addition to the normal supply of shell fragments from another source.

THE BOTTOM DEPOSITS IN CRANBERRY HARBOR

Since the grains of smaller sizes are evidently being carried off the beach it is of interest to see what is now present west of it in Cranberry Harbor. One sample was taken about a hundred yards from the shore, at low tide, at a depth of about eight feet. Mechanical analysis shows that only 3 per cent is more than 1 mm. in diameter, but 16 per cent is less than 0.125 mm. Sixty-nine per cent is in the grade between 0.25 mm. and 0.125 mm. This should be compared with the sample taken just above low-tide level on the adjacent part of the beach, only 0.2 per cent of which passed through 0.125 mm. The material on the bottom is obviously of much smaller average grade.

This sediment contains about 20 per cent of calcium carbonate. Inspection of the fragments in the various fractions shows that some of the calcareous material is furnished by dead shells, probably swept here from other parts of the bottom, although possibly *in situ*. All these are very small specimens of *Mya*, *Nucula*, and unidentified gastropods. These, although fairly common, do not make up a large part of the sediment. All are caught on the 1 mm. sieve and pass through that of 4.699 mm. Samples of all grades show much fragmental material, consisting of pieces of various pelecypods, gastropods, barnacles and *Strongylocentrotus*. These very likely were derived from the beach. The only organisms present which seem actually to have been living on the bottom were ostracodes and foraminifers, which although numerous, add little to the bulk of the sample. They were included in the material which gave a result of 20 per cent $CaCO_3$.

Another sample, taken about 300 yards off shore, has only 14 per cent $CaCO_3$. The physical characteristics are much the same as those of the one just described. A third sample taken about one-fourth mile off shore is much more calcareous, containing 21 per cent $CaCO_3$. This material is well sorted but coarse, for only 0.2 per cent is less than 0.125 mm. in diameter, Fifty-eight per cent is between 0.5 mm. and 0.25 mm., and only 4 per cent above 1 mm. The highly calcareous nature of this material is due in part at least to the enormous number of spines of sea urchins.

The final sample from the harbor, taken about halfway between Little Cranberry and Cranberry Islands, is also of somewhat coarse grain, in spite of the fact that it came from a depth of about fifteen feet, the greatest between the islands. Only 1 per cent is coarser than 1 mm., 4 per cent is less than 0.125 mm. and 50 per cent is between 0.25 and 0.125 mm. This sample contains only 9.5 per cent $CaCO_3$, a large part of this being due to the presence of dead shells, spines of *Strongylocentrotus*, and foraminifers, none of which had ever been on shore. A small percentage of the calcium carbonate was, however, derived from the beach,

for in the material less than 1 mm. in diameter, worn fragments of *Balanus* were present, and in that less than 0.25 mm., characteristic shreds of *Mytilus* were found. These made up only a very small proportion of the sample, which consists largely of small subangular grains of rock and angular quartz.

These dredgings are too few to afford any very definite results, but the presence of mud of the finest grain near the beach, and coarser material near the middle of the harbor suggests that there may be more effective transportation along a line extending from the "Gut" through the center of the harbor than there is near the beach. Possibly an eddy tends to leave material near the southern end of the beach, for the sand there is both finer grained and less calcareous than that at the northern end.

IS THERE DIFFERENTIAL SOLUTION OF THE SHELL FRAGMENTS?

When inspected under the binocular microscope, the fractions of many of these samples appear to show a steady decrease in amount of shell fragments from coarse to fine sizes. MacCarthy in his recent study of the sands along the Atlantic coast noted the same phenomenon.[1] He discovered, however, that when he removed the $CaCO_3$ by solution, and again screened the material, there was very little change in the proportion of the fractions to one another. From this he concluded that the shell fragments of various sizes were rather evenly distributed. One sample was run through to test this, the amount of $CaCO_3$ being determined for each of the fractions. It should be stated here that absolute accuracy is not claimed for our analyses. Samples of about 20 grs. each were dried, weighed, submitted to the action of cold, dilute HCl, the residue weighed, and the loss considered as $CaCO_3$. From the standpoint of the chemist this would seem to involve large errors, but when one reflects that it is mechanically impossible to so subdivide a sample as to get equal parts of shell in each portion, and that two samples taken a foot apart on the beach would have different compositions, the method seems accurate enough for this sort of material.

The sample analyzed was collected near the low-tide level on the most sandy part of the beach. At first sight, the analysis seemed to justify the ocular conclusion that the amount of $CaCO_3$ diminished with decreasing size. The 0.29 gr. caught on 3.327 mm. is 100 per cent $CaCO_3$; the 0.47 gr. on 2.362 mm. is 70 per cent $CaCO_3$, the 3.29 gr. on 1 mm. are 80 per cent $CaCO_3$, the 29.93 gr. on 0.5 mm. are 40 per cent $CaCO_3$, the 58.11 gr. on 0.25 mm. are 18 per cent $CaCO_3$, and the 9.38 gr. on 0.125 mm. are 12.5 per cent $CaCO_3$. The 0.39 gr. which passed through 0.125 mm. was ignored.

Since this sample contains 26.5 per cent $CaCO_3$, it is easily possible to calculate the proportion of the whole amount of that material in each fraction. We then see that the conspicuous fragments of the larger sizes are not so important as they appear. In reality, the greatest proportion of the total $CaCO_3$ is in the grades which

[1] *Am. Jour. Sci.*, vol. 22, p. 46, 1931.

pass through 1 mm. and are caught on 0.25 mm., 83.5 per cent of the whole being found there, although only 58 per cent of the total weight of the fractions in this size range was $CaCO_3$.

The proportions of the total $CaCO_3$ and of the total inorganic material in each fraction can be compared in the following table:

	Per cent $CaCO_3$	*Per cent Inorganic*
Above 3.327 mm.	1.0	0
3.327 mm.—2.362 mm. ...	1.2	0.2
2.362 mm.—1.000 mm. ...	10.0	0.8
1.000 mm.— .500 mm. ...	44.9	24
.500 mm.— .250 mm. ...	38.8	64
.250 mm.— .125 mm. ...	4.3	11

This comparison shows that calcium carbonate and the inorganic materials reach their maxima in different grades, which is not in accordance with MacCarthy's findings. This may, however, be due to the peculiar conditions which exist on this beach. All particles less than 0.25 mm. in diameter, whether of $CaCO_3$ or siliceous, are being removed from the beach, hence the rapid drop in the proportions of total $CaCO_3$ in sizes below that dimension is not necessarily an indication of more ready solution of the smaller sizes. Fortunately the dredging a hundred yards off this beach proves that a good deal of the material of finer grade remains near shore. A study of this sample shows that in the grade between 0.125 mm. and 0.074 mm., 11 per cent of $CaCO_3$ is present, whereas that which passed through 0.074 mm. contained 17 per cent. Since the whole sample contained only 20 per cent of $CaCO_3$, solution has evidently been no more effective in the finer than in the coarser grades. Before being analyzed the foraminifers and ostracodes were removed by decantation, so there was no calcium carbonate present which belonged to animals living on the bottom at this locality. The material caught on the 0.074 mm. mesh contained small rounded fragments of shells and a few shreds of *Mytilus*. That which passed through 0.074 mm. had fewer rounded fragments, but numerous shreds of *Mytilus*, and some spines from sand dollars. The rounded fragments undoubtedly, and the shreds of *Mytilus* probably, came from the beach. The sand dollar spines may have come from the beach, but they are much more abundant in the muds of the harbor than on shore.

One concludes from the above observations that the reason for the much lower proportion of $CaCO_3$ in the muds of the harbor than in the sands of the beach is that the small particles of shells withdrawn from the strand are spread over a very wide area, whereas the coarse fragments are concentrated in a very limited site on shore.

THE ORIGIN OF THE BEACH

Three factors combine in the making of this shell beach—first, a situation unfavorable for the production of mineral sand; second, conditions favorable for the growth of molluscs and barnacles in vast quantities; and lastly, peculiar hydrographic surroundings.

The islands of this part of the coast are composed of hard igneous and metamorphic rocks on which wave attack has made little impression. All beaches except that under discussion are of the cobble and pebble variety,

largely the result of the washing out of till in small local areas. The sand and pebbles mixed with the shell-sand on the beach at Islesford undoubtedly originated from two small deposits of till, represented today by patches of cobble stones just about low-water mark.

The passage between Great and Little Cranberry, known locally as the Gut, is shallow, with a broken bottom and numerous ledges which are bare at low water. This shoal area extends a mile or so seaward, and swings in a broad arc around the southeast point of Great Cranberry. There is considerable tidal current through the Gut, and although no accurate data are available the velocities at the peak of flood and ebb cannot be far from two knots. The nature of the bottom, and the large quantities of water which pour over it daily make very favorable conditions for the growth of molluscs, sea urchins, and barnacles.

During gales from the east and southeast the sea breaks heavily over this whole area, as the greatest depth is only fifteen or sixteen feet at mean low water. Vast quantities of shells are ground up and swept through the Gut into Cranberry Harbor by the seas, which of course become waves of translation on striking this shoal. Exceptionally heavy blows tear up thousands of living individuals near shore and sweep them along with the sand that has been produced farther out. At low water large patches of shell-sand are visible all over the bottom of the Gut. The whole thing operates as a large mill and the product is swept into the relatively quiet waters between the islands. The ocean swells are of course greatly reduced in size and velocity on passing through the Gut, nevertheless they possess sufficient force to spread the material out over the bottom. Part of each wave acquires a certain northerly component on rounding the point of Little Cranberry, and much of the shell and shell-sand is carried in that direction, to be dropped in shallow water near shore.

A sample dredged from one of the patches of sand in the Gut about one hundred yards off the rocks at the south end of the beach, contains 85 per cent $CaCO_3$, being made up chiefly of fragments of *Mytilus*. As might be expected, the material is coarse, 67 per cent being more than 1 mm. in diameter—the greatest quantity in any one grade—that between 2.362 mm. and 1 mm. being 38 per cent. Only 0.8 per cent was smaller than 0.25 mm. in diameter. The part above 4.699 mm. consists of pebbles and fragments of *Mytilus*. The organic material which passed through this sieve and was caught by 2.362 mm. contains 11.7 gr. of *Mytilus*, 0.73 gr. of *Balanus*, and 0.78 gr. of fragments of unidentified pelecypods and of *Strongylocentrotus*. In the next smaller grade, caught on 1 mm., *Mytilus* and *Balanus* are almost equally common, whereas on the 0.5 mm. sieve fragments of *Mytilus* are most abundant, spines of *Strongylocentrotus* next, and *Balanus* third in importance. Fragments of these same organisms are present in the portions of smaller sizes, but in these inorganic grains predominate over the calcareous ones.

The inner or shell beach is built by a

different set of waves from that which produces and distributes the material. Completely protected from the open gulf, the west and northwest winds are the only ones which can act upon it effectively. Four miles is the greatest stretch of open water, and although a steep chop can be developed during heavy blows, the waves are, of course, not comparable in size and power to those on the outer side of the island. Wave action is sufficient, however, to build a low beach ridge, the top of which is four or five feet above mean high water. The ridge is overflowed when the exceptional spring tide is accompanied by the right wind conditions. Wave action, however, is not sufficient to destroy completely the fragments which are derived largely from thin shells. Neither is it sufficient to erode the bottom to any considerable distance off shore, thereby adding inorganic detritus to the beach. The "mud line," as we have seen, is in very shallow water. Some material is undoubtedly derived from organisms living along the beach, but by far the greater part comes from outside.

The outer beach, as mentioned before, is a high barrier of well-rounded pebbles and cobbles, standing ten feet or more above mean high water. It would seem that much shelly material must be cast on this beach, but that, due to the violence of the wave action, it is destroyed at once by the wear of the abundant inorganic material. In fact as we progress further to the east along the outer beach and come under the lee of certain off-shore ledges which break the full force of the southeasters, shell-sand is noticeable among the pebbles, and the barrier is not so high. A sample taken at low water near the Coast Guard station has 17 per cent $CaCO_3$. The tombolo portion of this beach is being driven back over the marsh, and as the material appears to be largely derived from erosion of the bottom, the supply is fairly limited.

The shell or inner beach, on the other hand, appears to be slowly growing. Behind and parallel to the present ridge there is a considerable area of fairly level, well-grassed ground on which one and possibly two old beach ridges can be traced. On this level area several large sheds for yacht storage have been built. At one place there is a small graveyard, the oldest on the island, with one grave dating from the middle seventeen hundreds. Beneath the thin layer of humus is shell-sand. Its total thickness is unknown, but according to Mr. Arthur Fernald of Islesford, it reaches a depth of six or seven feet, to the bottom of the graves at any rate. The easy digging afforded by this material, as contrasted with the rocky soil elsewhere, induced the early settlers to pick this spot for a burying ground. The formation slopes gently to the level of the swamp, in contrast to the outer or cobble beach, which has a steep back slope, caused by overwashing of very coarse material. Several mosquito drainage ditches have recently been cut in this swamp to the depth of two feet or more and the bottoms of all of them are paved with shell-sand where the muck has washed away.

From the foregoing it is obvious that this shell beach is due to a com-

bination of factors, an upset in any one of which would eradicate it. It is the result of special conditions, and a nice balance of forces is required to maintain it. Shell must be ground up in large quantities and placed within the reach of a set of waves strong enough to build a beach, but not strong enough to erode the bottom or coast line. In that event the shell-sand would be smothered with inorganic débris and destroyed by excessive abrasion. When the outer tombolo is breached, as must happen in a short time, geologically speaking, if sea level remains constant, the balance will be upset, and the shell-tombolo will be obliterated.

OTHER SIMILAR BEACHES

One of the principal reasons for this article is to bring forth information as to the existence of other similar calcareous beaches in extra-tropical regions. No attention seems to have been paid to this subject.

There is, of course, one which is rather well known, that at Dog's Bay on the southwestern coast of Galway, Ireland. This beach is made up chiefly of shells of foraminifera which are stranded there because of a fortuitous combination of directions of local currents and the North Atlantic drift. Once again, it is the result of special conditions.

Another calcareous beach, which has been visited but not studied by the senior writer, is that at English Bay, Vancouver, B.C. In the upper part of this bay, just west of the popular bathing beach, there is a raised beach in which fragments of shells are very abundant. They are washed from this old deposit, to mingle with those of the modern waters, forming a very calcareous sand in a small area. Recently built sea walls and other improvements retard the study of this example, but it is hoped that someone in the neighboring university will describe it.

A third shell beach, known to us only by hearsay as it were, is on the island of Herm, one of the smaller Channel Islands, between Guernsey and Sark. Of this the eleventh edition of the *Encyclopaedia Britannica* remarks "Herm possesses the remarkable phenomenon of a shell beach, or shore, half a mile in length, formed wholly of small shells, which accumulate in a tidal eddy formed at the north of the island" (article not signed).

Further information about these and others, will be welcome.

SUMMARY

The results of this preliminary investigation seem to indicate that a deposit containing from 60 to 70 per cent of broken shells may accumulate on a beach, even in a region of cold water, if: (1) hydrographic and physiographic conditions are exceptionally favorable for the concentration within a limited space of shells derived from a large area; (2) the beach is subjected to only moderate wave action; and (3) the supply of inorganic detrital material is small.

The abundance of shell beaches in tropical and subtropical regions, and their scarcity in temperate or arctic regions, has led to a rather general supposition that the temperature of the

water was an important factor in the formation. The occurrence of the few beaches which have been mentioned in this paper does not prove that temperature has no influence. Rather only that under favorable conditions shells may accumulate in spite of relatively cold water. The most obvious necessity for the formation of a shell beach is that the supply of inorganic detrital should be small. Because of the difference in hardness of the materials it seems probable that shells and shell-sand mixed with inorganic detritus can stand very little intensive wear. The shells are rapidly ground to powder and drawn off the beach by wave action. Conversely, a beach of pure shell-sand may stand the full sweep of the open sea if it has only material of its own hardness to grind against.

It so happens that at the present time, soft glacial or Tertiary deposits are so abundant in temperate zones that pure accumulations of shells can hardly be expected. Geologically, present-day conditions are unusual. Is it not possible that before the Pleistocene, shell deposits of greater purity might have accumulated in higher latitudes than at present? The question is of considerable interest in its bearing upon the origin of limestone.

The beaches just described are too small to have any importance in its production. Fragments, particularly those of smaller sizes, are being withdrawn by the waves and spread about, but, as has been shown by the dredgings, these make up only a relatively small portion of the sediment accumulating on the bottom. If the beach were elevated and cemented, or rapidly submerged it would produce a small lense of impure coquina-like limestone in the midst of materials of other nature. However, could such beaches have formed along large extents of shore in northern or southern latitudes before Glacial times, they would have been just as important a source of limestone as are beaches in the regions of warm water today.

If the muds of Cranberry Harbor could be preserved as they are today, they would produce a highly fossiliferous fine-grained calcareous sandstone. Such shallow-water deposits are, however, as little apt to be preserved as is a beach deposit.

Since so much calcareous material is, at the present time, drifting shoreward, we can only speculate as to what the ultimate contributions to permanent geological formations will be, presupposing no change in sea level. If the mill continues to operate in the same manner for a long period of time, and the finer materials continue to be deposited in the deeper water near the rocky shores of Mt. Desert, a considerable deposit of calcareous material will eventually accumulate there. The material will become increasingly calcareous, for the most of the till within reach of wave attack has already been removed. The shell-sand therefore must increasingly predominate over siliceous sand in the future. If civilization, printer's ink, and modern paper endure so long, we suggest that our successors, some ten thousand years hence, resurvey this area. Although not a full explanation, this occurrence is suggestive in connection of the not uncommon succes-

sion in the Paleozoic of conglomerate, sandstone, calcareous sandstone, and limestone. Such a succession is a cycle truly, but may be a cycle of events in time, not necessarily of changes in sea level.

The point of chief interest is perhaps the solubility of shells in cool or cold sea-water. Theoretically there should be considerable solution, more on small particles than on large. The few observations made during the present study have no bearing on the total amount of solution, but suggest that the smallest grains are just as resistant as the larger. There does seem to be some way in which a warmer temperature favors the accumulation of limestone. Possibly it is merely in its control of organic life, for warmth is certainly favorable to the growth of corals, alcyonarians, tube-forming worms, calcareous algae, thick-shelled pelecypods, and gastropods. Hence a locality situated in the region of warm seas, if it be one where little inorganic detrital material is available, is more favorably situated for the production of shell beaches than any area in more northern districts.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 2, NO. 2, PP. 63-67, PL. 3,
AUGUST, 1932

A CALCAREOUS BEACH AT JOHN O'GROATS, SCOTLAND

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A chance visit to John o'Groat's recently introduced the writers to a phenomenon whose existence the senior author, at least, had deemed impossible. This is a beach-sand made up almost entirely of fragments of calcareous shells, in latitude 58° 39′ north.

This beach is located at the eastern end of the northern coast of Scotland, extending for nearly two miles, from a small point called Huna Ness to Duncansby Ness, which is about three-fourths of a mile east of John o'Groat's Hotel. Throughout its length it is composed of a white glistening shell sand, comparable to that of the beaches of Bermuda or of islands within the tropics.

It is true that the climate of this region is ameliorated by the influence of the Gulf Stream. Surface temperatures of the sea vary from 41°F. in January and February to from 54° to 55°F. in July and August. The highest temperatures are the same as on the coast of Maine, but the lowest are some 7°F. higher than the lowest in that region. The invertebrate faunas of the two regions are similar, but that on the coast of Maine is purely boreal, whereas the shells of the north coast of Scotland are partly boreal, partly of a more southern derivation. As compared with the shells whose fragments are included in the sand on Little Cranberry Island, Maine, those at John o'Groat's are notably thick. Possibly there is a relationship between the slightly higher temperature and the greater thickness of the shells.

The calcareous sand is made up of large and small fragments of shells of invertebrates of species still living in the vicinity. Mr. W. J. Clench has identified *Buccinum undatum, Patella vulgata,* and *Tritonofusus gracilis* among the few specimens we picked up in the sand near the low-tide level. We also noted numerous shells of *Glycymeris glycymeris* and *Modiola modiola* while at the locality.

This sand is obviously subjected to considerable abrasion and sorting by waves. Most of the fragments, although flat, have the edges well rounded and the whole surface polished.

The material is all rather coarse-grained, but is much finer between tides than near the high-water level. A sample from the latter position has 12.8 per cent larger than 3.327 mm. in diameter, and 87 per cent less than that, but above 0.5 mm. Only 0.2 per cent passed through the 0.5 mm. sieve.

A sample collected between tides consists of much smaller fragments, 61 per cent passing through the 1 mm. sieve and being caught on the 0.5 mm.

Both very coarse and fine-grained materials are practically absent, the fragments above 2.362 mm. and those below 0.25 mm. together making only 1 per cent of the total.

Analysis of this sand shows that it contains slightly over 97 per cent $CaCO_3$. The residue after the calcium carbonate has been removed consists largely of small, rounded fragments of sandstone, numerous angular grains of quartz, some broken artificial glass, and considerable organic debris. A very few well rounded grains of quartz are present. More were seen in some of the sieved samples.

The presence of fresh shells, both entire and broken, but retaining the color, shows that the deposit on the beach is now receiving additions from the sea. Further evidence is supplied by the rather numerous fragments which, although well worn, retain traces of the periostracum. A second source of supply is, however, present in a low bluff which faces the beach throughout most of its length. It rises about seven or eight feet above the beach, with its base well above the limit of ordinary high tides. That it is not now subject to any active erosion is shown by the fact that most of its steep face is grassed over. The shell-sand extends to the foot of this bluff, which we were led to investigate by the fact that near it large, nearly complete specimens of *Buccinum* were more common than on any other part of the strand. Fortunately, a large fresh artificial excavation allowed examination, which showed that the bluff is cut in a stratified accumulation of shell-sand of the same nature as that on the beach. Analysis of a sample from one of the layers of finer grain shows much the same size characteristics as the sand between tides. Only 1 per cent is coarser than a diameter of 2.362 mm., 52 per cent is less than 1 mm. and larger than 0.5 mm., and 95.4 per cent was passed through 2.362 mm. and was caught on 0.25 mm. Three and six-tenths per cent passed through 0.25 mm., a somewhat larger proportion than on the beach. Chemical analysis shows 95 per cent $CaCO_3$. The insoluble residue consists chiefly of angular quartz sand with some rounded quartz grains, rounded fragments of sandstone, and a good deal of peat.

One layer about halfway up the bluff is made up very largely of bleached, more or less worn, but nearly entire shells. *Buccinum* was by far the most common, but Mr. Clench has also identified *Thais lapillus, Gibbula umbilicata, Trivia europaea, Patella vulgata, Glycymeris glycymeris,* and *Hinnites pusio* from this layer. All these are species now living in the waters of this region.

Although this bluff is not now subject to the attack of the waves, its steepness shows that it has been so at no very distant time. There is good reason to believe that it has contributed largely to the material on the beach.

ORIGIN OF THE MATERIAL IN THE BLUFF

This deposit in the bluff has been described briefly by C. B. Crampton,[1] who wrote as follows:

[1] The Geology of Caithness, *Memoirs Geol. Survey, Scotland,* 1914, p. 140.

EXPLANATION OF PLATE 3

FIG. 1.—A view looking northeast from the pier at John o'Groat's. The white sand of the beach lies unconformably on the edges of layers of Old Red Sandstone. The low bluff in the background is a deposit of shell fragments.

FIG. 2.—A vertical section in the face of the bluff, showing the stratification in the raised deposit, and the large specimens of *Buccinum* in one of the layers.

Quantities of shells are driven ashore and lodge behind the shore reefs between John o'Groat's and the Bay of Sannick. They are chiefly deeper water, rock, and *Laminaria*-dwelling species, including *Modiola modiola, Buccinum undatum, Emarginula, Trivia europaea, Pectunculus glycymeris, Capulus hungaricus, Helcion pellucidum,* and others, with numberless plates of a large barnacle. *Patella vulgata* is, however, abundant and derived from the shore reefs. A great accumulation of the shells in a comminuted condition backs the shore for the whole distance and also extends inland for about 100 yards, as a thick deposit probably in the nature of a raised beach. . . .

The great mass of broken shells backing the present beach [i.e., between high water level and the base of the bluff] is undoubtedly the accumulation of a very long period, and was probably formed during the retreat of the sea from the 5-foot raised beach, but it now suffers erosion during storms, which points to a late advance of the sea on the land. Large accumulations of broken shells, such as those at John o'Groat's, point to an off shore rocky bottom kept clear of sediment by strong currents or wave action. Small quantities of shell sand accumulate behind the shore reefs at Ackergill, Keiss, and elsewhere, but the materials in these cases consists chiefly of fragments of shallow-water rock-dwellers, as *Littorina* and *Patella,* or sand-living lamellibranchs as *Tellina* and *Mactra* from the sandy bottom beyond the reefs.

We agree with Crampton that the material in the bluff above the present strand does represent a raised beach, but only the landward part of one. It appears to correspond to the inner or overdash platform which Raymond and Stetson describe from the occurrence on Little Cranberry Island, Maine (see *This Journal,* Aug., 1932). If so, it must have been formed when the water stood from five to eight feet higher in relation to the land than it does at present. The surface of this material may well have been modified by the action of the wind, but the presence of a layer of large shells, many of which weigh from 20 to 30 grams, and the regular bedding preclude the possibility of an eolian origin for the whole deposit. It seems to have been built up by exceptional storms which carried material beyond the zone of influence of ordinary waves. It is stratified by reason of the varying coarseness of the fragments transported in different storms.

The writers are inclined to believe that it at one time extended farther seaward than at present, and that a great deal of it has been destroyed, for Dr. R. McDonald, who has dredged in waters off this coast, tells us that such shell sand is encountered on the bottom in places. During a period of sinking coast, a beach would move landward, the outer face being constantly destroyed, the coarser material pushed inward and the finer withdrawn by the sea. During a period of still-stand, it might move inward or outward, depending upon the supply of material and the force of the waves. In the present instance the supply of material was small, consisting as it did of broken shells. With emerging land, with small supply of material, the "overdash" deposit would be small, there would be some destruction of the strata formerly accumulated above high water, and the resultant appearance would be exactly such as is now presented on the beach at John o'Groat's. We believe, therefore, that the deposit in the bluff represents an accumulation during the time when the

land stood five or more feet lower than it does at present, and that the present beach was formed during the emergence.

WHY THE CONCENTRATION OF SHELLS AT JOHN O'GROAT'S?

So far as we have been able to learn, this beach is unique on the northern coast of Scotland. Such others as we saw between John o'Groat's and Thurso consisted in the main of quartz sand, and there is no record of a shell beach farther west.

As all navigators know, the Pentland Firth is a most extraordinary place, beset with tidal currents which almost defy analysis. The beach in which we are interested is on the southern border of the narrower of the two channels into which the island Stroma divides this firth. The so-called "Inner Sound," south of Stroma, has in its center a current, which at certain phases of the tide, reaches a velocity of five knots per hour. This current does not, however, affect the shore of John o'Groat's, but, passing north of it, produces an eddy which, while the current is running eastward, is deflected toward that shore. West of Stroma, hence west of the beach, an eddy sets westward, and east of the beach is the dreaded bore of Dunkansby. All currents, then, tend to push sea-borne material in toward the shore of John o'Groat's. It is very probably true then, that shells detached from rocks over a considerable area in this vicinity would be cast upon this beach. Rocky ledges contribute many shells; others may be driven in from reefs, islands, and ledges all along the Inner Sound. That shells are abundant even where the sands are siliceous, is well attested by the abundance of their fragments in the dunes on the coast at Dunnet Bay, some sixteen miles west of John o'Groat's. A sample collected there has over 13 per cent $CaCO_3$.

The "Coast Pilot," compiled and published by the British Admiralty, and reproduced in the United States, is the authority for the statements above in regard to the currents. For any geologists who do not realize the amount of information to be had from this source, we might quote the following:

> From Huna Ness eastward the coast is chiefly composed of broken shells, with rocky ledges, dry at low water, extending off 200 yards. . . . Dunkansby Ness . . . one half mile eastward from John o'Groat's House, is a low grassy point composed of broken shells. From it rocky ground extends over one mile northward.

These unsigned but accurate and informative publications should be consulted by every geologist interested in strands.

Hydrographic conditions, although by no means fully known to the writers, do seem to be favorable for the accumulation of shells on this coast. According to the "Coast Pilot," the prevailing winds of the region are from the southeastward, round south to westward. Except for the latter, these would be off shore winds. On the average about five really bad northwesters occur in each year. To a certain extent the force of west and northwest winds is broken by Dunnet Head, Stroma, and particularly by the contraction of

the Inner Sound to a width of only a little more than a nautical mile between Point St. John, with its Men of Mey, and the southern shore of Stroma. Even more effectual in breaking up long waves are the rapidly moving currents and eddies in the Sound. Compared with the coast west of Dunnet Head, this southern beach of Pentland Firth is in a protected area, in some degree comparable to the situation at Cranberry.

THE NON-CALCAREOUS MATERIAL

Although the country rock about John o'Groat's is relatively soft Old Red sandstone, peculiar conditions combine to make the supply of siliceous sand at this beach almost negligible. Because of its protected position, this is one of the few places where the north of Scotland is not bordered by sandstone cliffs. The reefs parallel to the beach are well smoothed, partially protected by kelp, and free from cobbles and boulders which would tend to grind them. They are therefore but slightly subject to erosion. The land which slopes gently upward from the beach is heavily covered with peat, which checks subaerial erosion, and prevents the transportation of clastic materials to the sea.

John o'Groat's, like Little Cranberry, is a special case. So long as it exists, it will be a source of supply of fine-grained calcareous material. If that is trapped, instead of being spread over a large area, it may eventually become an impure limestone, or at least, a calcareous sandstone, with a cool water fauna.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 2, NO. 2, PP. 68-73, FIGS. 1-9,
AUGUST, 1932

GLACIO-LACUSTRINE SEDIMENTS REWORKED BY RUNNING WATER[1]

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ABSTRACT

Extensive areas of glacio-lacustrine sediments were exposed by the partial draining of a glacial lake near Ely, Minnesota. A deep gully was excavated in the sediments by the draining of a bay of the lake. Samples of the lacustrine beds were collected and compared with samples taken from a delta built in the present remnant lake. The soluble constituents are limited to finely varved clays in the lacustrine bed, and none were retained in the delta sediments. Heavy minerals are confined to the finer size-grades in the lacustrine beds and show a resorting by currents in the delta sediments.

INTRODUCTION

Bass Lake and Low Lake are located about four miles north of Ely, Minnesota. They occupy a long, narrow basin that was gouged out of pre-Cambrian crystalline rocks during Pleistocene glaciation (fig. 1). Both lakes are in the same rock basin, but they are separated by a ridge of glacial

[1] Published with the permission of the Director of the Minnesota Geological Survey.

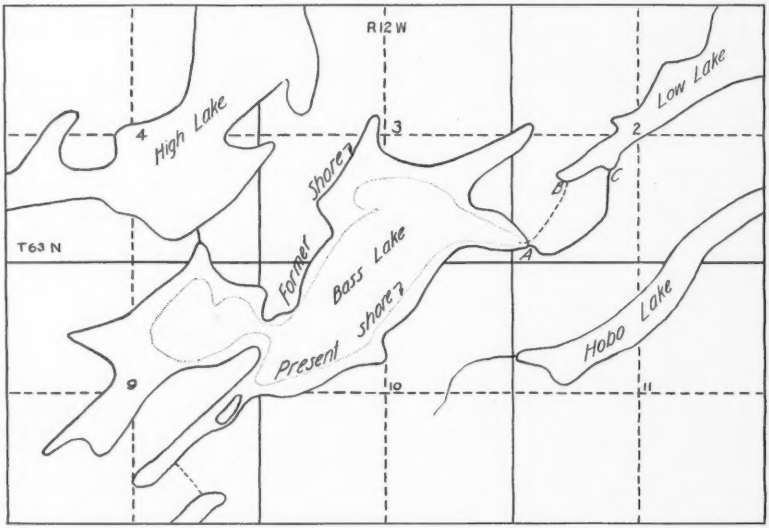


FIG. 1. Outline map of Bass Lake showing the position of its former and present shorelines and its relation to Low Lake.

gravel that serves as a dam between them. As the glacier receded, the outlet from Bass Lake was established over a low point in the rim of the basin at the east end of the lake (A, fig. 1). The short stream (A-C) connecting Bass Lake with Low Lake cut its channel to the bed rock of the margin of the glacial basin, and the rate of deepening of the outlet and the consequent lowering of the lake level was therefore greatly retarded. The outlet of Low Lake was lowered more rapidly, until eventually the water level in Bass Lake stood approximately sixty feet above that in Low Lake. The horizontal distance between these two bodies of water was less than a thousand feet, with only a heap of glacial gravel separating them (fig. 2). This gravel embankment retained the waters of Bass Lake throughout all of post-glacial time, until recently when lumbermen built a sluiceway connecting the two lakes. A short time after the construction of the sluiceway, seepage channels were established through the gravel beneath it, until

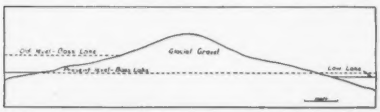


FIG. 2. Profile showing the relation of the old level of Bass Lake to that of Low Lake.

suddenly, the dam of drift was swept away and the gravel deposited in the west end of Low Lake. Bass Lake was lowered fifty-five feet in less than ten hours. (fig. 2). During that short interval of time, thousands of tons of sediments were transported and redeposited, and large areas of glaciolacustrine sediments were exposed on the lake floor.

The largest areas of sediments are exposed along the north shore of the

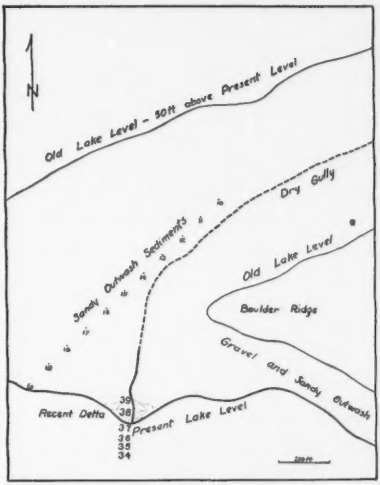


FIG. 3. Outline map showing the locations from which samples were taken on the exposed lake bed.

lake. Here the floor of the lake basin has a gentle slope to the south and a zone over a thousand feet wide is exposed above the present water level (fig. 3). Several bays to the north and northeast in sections 2 and 3 are completely drained. The south shore is outlined by steep rocky slopes and cliffs of massive igneous rocks and therefore, only a long narrow portion of the old lake basin is drained along its south margin.

The northeastward extension of Bass Lake into section 2 (fig. 1) had a depression in its floor, the draining of which led to the formation of a

gully ten to fifteen feet deep in the glacio-lacustrine sediments between the depression and the present lake shore. Some of the sediments excavated from the gully have been redeposited as a delta in the lake (fig. 3).

NATURE OF SEDIMENTS

The exposed sediments are mainly medium-grained glacial sands. The succession of beds as exposed in the gully (fig. 3) indicates a period of coarse clastic deposition followed by

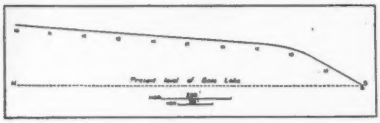


FIG. 4. Profile of lacustrine beds along the line of samples shown in figure 3.

a recession of the ice to a position from which only fine silts and clays reached the lake. These fine silts are represented by varved sediments about six feet thick. The clays grade upward into fine sands and these are overlain by cross-bedded and laminated medium-grained sands. These upper sandy beds indicate a period of re-advance of the ice to a position from which coarser sediments were again carried into the lake basin.

A series of samples taken from pits spaced every 100 feet over the surface of the exposed sands shows the textural range plotted in Figure 5. Sample 10, taken at the greatest distance from the present water level, contains the coarsest sediment. Samples 10 to 14 show a graduation from a coarse to a finer texture. In sample 18 a higher ratio of coarse to fine grains is noted. This increase in size of grain may be due to two factors; (1) the position at which the sample was taken on the profile of the lake floor (fig. 4), and (2) the removal of finer fractions by erosion since the lake bed has been exposed above water level. Samples 19 and 20 are fine-grained. In the succession of sediments referred to above, sample 19 represents the level of the transition zone between typically varved clays and the cross-bedded sands above, whereas sample 20 was taken from the thinly laminated clays.

A composite sample made by taking equal amounts of samples 10 to 20 inclusive, shows a size-grade distribution as plotted in the lower diagram of the right column in Figure 5. Most of the grains in the sediment are finer than .5 mm. in diameter. The grains are very irregular and angular in shape and show all the characteristics of glacial material resulting from the crushing and grinding of fresh, unaltered rocks. Most of the grains are fragments of quartz and orthoclase and consequently the sediment is light in color.

The heavy minerals are uniformily distributed and constitute 6.25 per cent by weight of the total sediment. The most abundant minerals are hornblende and magnetite. In the coarser samples (10 to 12) very few heavy grains are found in the fractions finer than 1/16 mm. In sample 14, however, 11 per cent of the fraction finer than 1/16 mm. is composed of heavy minerals. From 14 to 20 all of the samples contain appreciable amounts of heavy minerals in the finer fractions. This distribution indicates that the fine-

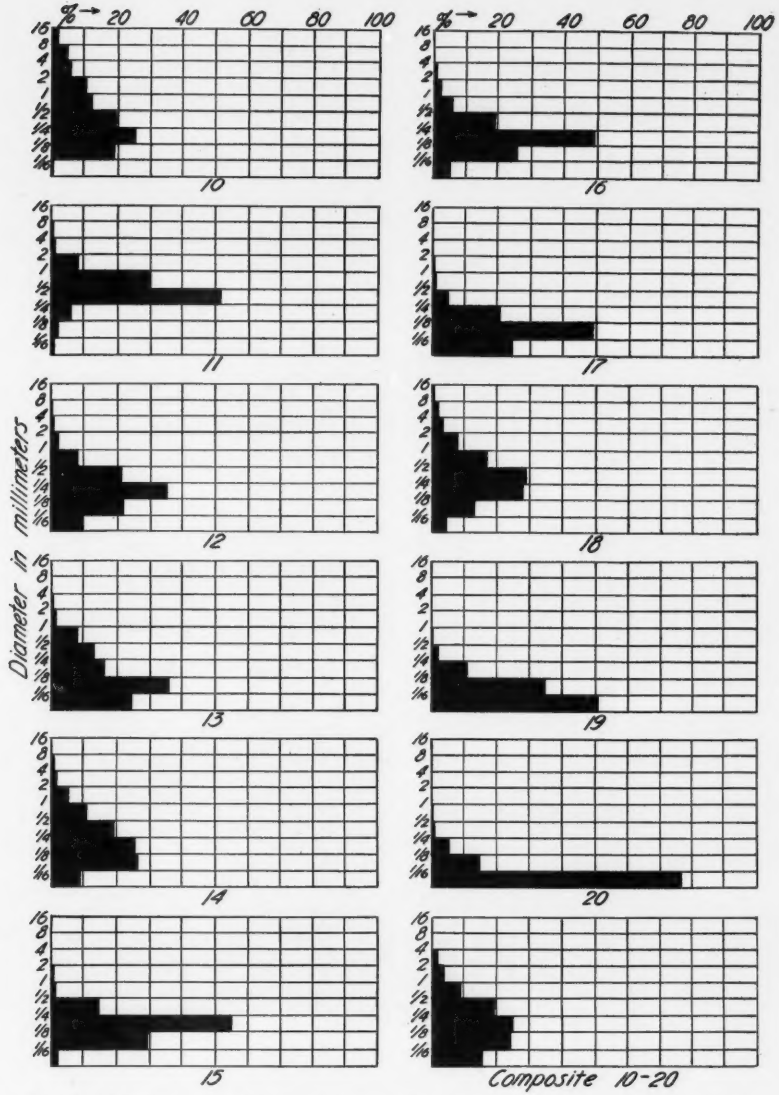


FIG. 5. Diagrams showing the textural distribution of the lacustrine sediments.

grained heavy minerals were carried further from shore and concentrated in the zone on the profile of the lake floor, from which samples 14 to 16 were collected.

The ratio of heavy minerals to each other as indicated in Table 1 shows that hornblende predominates in the coarse fractions, whereas magnetite is the most abundant in the finest fractions. No magnetite is found with the grains that are greater than 1/8 mm. in diameter. This distribution is undoubtedly due to the greater specific gravity of magnetite. Only very fine grains of magnetite were carried out into the quiet water of the glacial lake to be deposited with the lacustrine sediments.

TABLE 1. HEAVY MINERAL ANALYSIS OF GLACIO-LACUSTRINE SANDS
Per cent by Number of Grains

Mineral	Size in mm.			
	$\frac{1}{2}$–$\frac{1}{4}$	$\frac{1}{4}$–$\frac{1}{8}$	$\frac{1}{8}$–$\frac{1}{16}$	$\frac{1}{16}$
Magnetite	—	—	1	40
Hornblende	96	94	84	37
Zircon	1	2	7	6
Tourmaline	—	1	1	—
Titanite	1	—	5	3
Apatite	—	1	2	14
Garnet	1	1	—	—
Biotite	1	1	—	—

Soluble carbonates are entirely absent in the coarser sediments. Each size-grade of samples 10 to 19 inclusive was treated with HCl with no appreciable loss of weight and no evidence of effervescence. Sample 20, which represents the stratum of varved clays, is composed of such finely-textured material that nearly 80 per cent is less than 1/16 mm. in diameter. This fine sediment contains 4.1

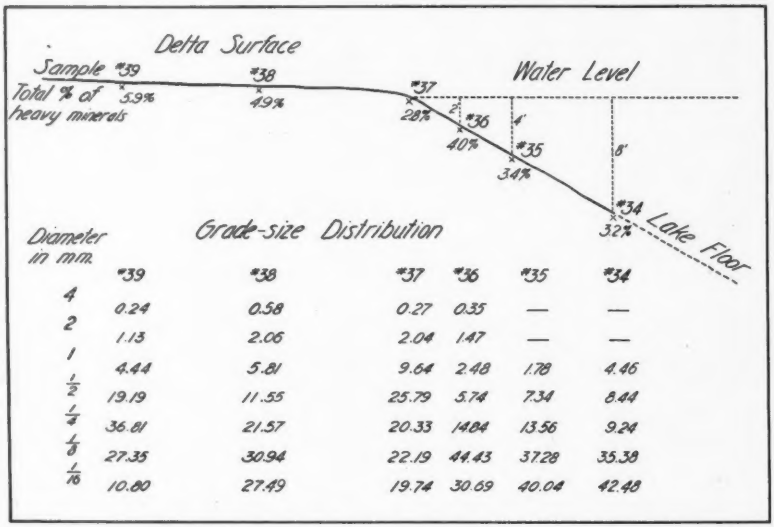


FIG. 6. Diagram and table showing the texture and distribution of sediments in the delta derived from the lake beds.

per cent soluble carbonates. The redistribution of the carbonates in the delta sediments derived from the glacio-lacustrine beds will be discussed in a later section.

REDISTRIBUTION IN DELTA

The lacustrine sediments excavated from the gully shown in Figure 3 were transported and redeposited in a small delta where the stream discharged in the present remnant lake. The locations from which the samples were taken from the delta are shown in Figure 6. A diagram of a composite sample made from equal amounts of samples 34 to 39 inclusive is included in Figure 7. By comparing it with the composite of samples 10 to 20 plotted opposite it in the same figure, it is evident that the two composite samples represent the same textural type of sediment.

A study of the size-grade distribution of the delta series of samples brings out a number of facts that reflect the influence of the sorting action of running water. By comparing samples 38 and 39, both taken from the upper surface of the delta, the most outstanding difference is noted in the fractions finer than 1/16 mm. in diameter. Number 38 contains nearly three times as much as number 39. This increase is due to sheet wash over the flat surface of the delta, carrying the fine material from the mouth of the gully and depositing it further out on the delta surface. Sample number 37, at the water's edge, shows a

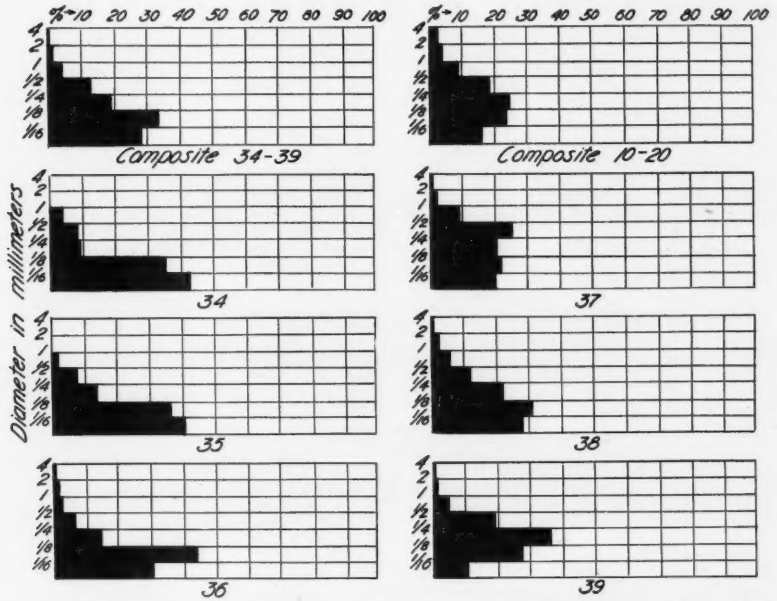


FIG. 7. Diagrams showing the textural distribution of the delta series of sediments.

marked increase in the fractions ranging from 1 to .25 mm. in diameter, whereas its material finer than 1/16 mm. is correspondingly less abundant. This difference may be explained by the undertow carrying the finer fractions to the deeper water down the slope of the lake floor and a lag of coarse sediments at the water's edge. Samples 34 to 36 are composed mainly of grains smaller than 1/8 mm. in diameter.

The distribution of heavy minerals in the delta sediments also shows the sorting effect of running water. By ignoring sample number 37 which has been reworked by wave action, the series shows a progressive decrease in the amount of heavy minerals from the mouth of the gully to the lake floor under eight feet of water. The percentage of heavy minerals for each size-grade is indicated in Figure 8. Samples 34 and 35 contain less than 1 per cent of heavy minerals in their coarse-textured fractions. Heavy grains are fairly abundant in the finest fraction but the percentage for the

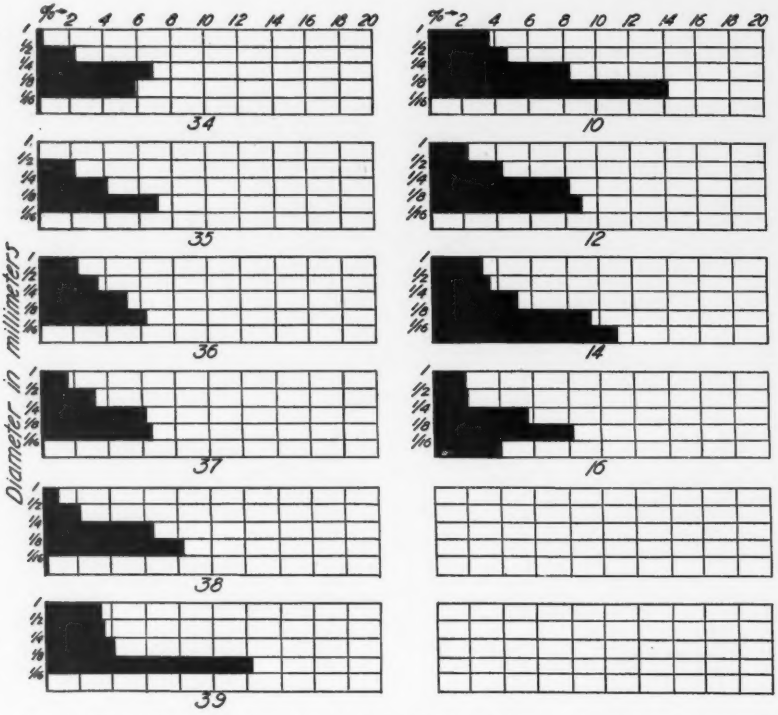
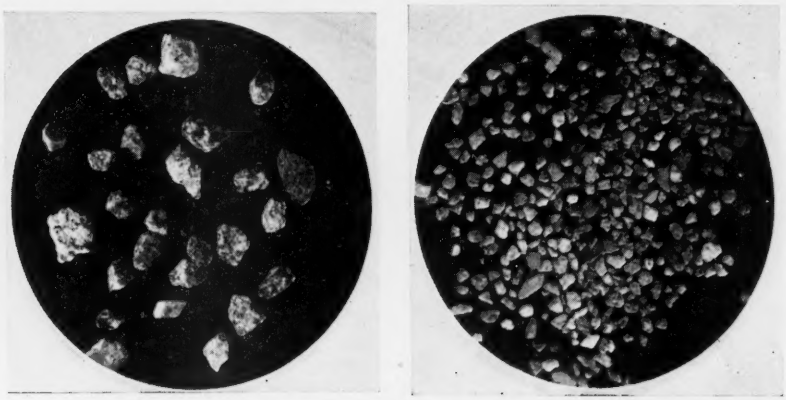


FIG. 8. Diagrams showing the size-grade distribution of heavy minerals. The percentage indicated represents the per cent by weight of heavy minerals in the screen size designated.

fraction is low due to the high percentage of fine light grains in the sample as a whole. The total precentage of heavy minerals in sample 37 is lower than either 38 or 36. Wave action has undoubtedly aided in transporting the finer heavy grains to the quiet water further from shore. Sample 35 shows an increase in heavy grains in the 1/8 to 1/16 mm. fraction which may represent material transported from the water line where sample 37 was taken.

Soluble carbonates are entirely absent in the delta sediments. The 4 per cent of fine grained carbonate particles associated with the varved clays in the original glacio-lacustrine beds were all carried beyond the depth and distance from the shore that was sampled for the delta series.



A B

FIG. 9. Photomicrographs of Bass Lake sediments showing the angularity that characterizes glacial sediments. (Ax10, Bx3.)

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 2, NO. 2, PP. 76-88, FIGS. 1-6,
AUGUST, 1932

A TEXTURAL VARIATION SERIES OF BEACH SANDS FROM CEDAR POINT, OHIO

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ABSTRACT

Eighteen samples of beach sand were collected at half-mile intervals along the shore of Cedar Point spit and connected mainland near Sandusky, Ohio. The samples were screened and treated with acid and the per cent of sand and carbonate in each size-grade was computed.

A marked decrease in size-grade of the sand from the mainland beach to the far end of the spit is shown by the shifting of the maximum grade towards the finer sizes and by a decrease in both the median size and the equivalent grade. There is no appreciable increase in degree of sorting in the same direction as indicated by the grading factors determined from the cumulative curves. Secondary maxima of the samples on the beach near the mainland or on the mainland beach appear to be due to loading of the samples with material from nearby wave-cut cliffs or to the inclusion of lag concentrates in the sampling.

The carbonate at first decreases and then increases through the series. In the individual samples it is found to make a larger proportion of the coarse and fine grades than of the intermediate grades. No satisfactory explanation of the latter relationship is known to the writers.

The decrease in size-grade is not due to abrasion to any important extent but either to a selective sorting by the littoral currents or to some factor in the environment, such as the subaqueous slope, that changes progressively from place to place along the beach.

A group of sediments which are genetically related and which have evolved from a common source material may be termed a *variation series.* Sediments collected from the same stream, the same beach, or the same dune area constituted such a variation series. The properties of the sampled materials vary from sample to sample, usually in some definite way which may be a function of the stream gradient, distance of transportation, or orientation of the shore line to wind direction. The sediments may be differentiated into several distinct sedimentary types so as to form a *differentiation series,* or they may evolve in a regular way from one type to another forming a *linear series.*[1]

The beach sands selected for study constitute a linear series that shows systematic variations from sample to sample which may be quantitatively measured and graphed. Quantitative data on beach sands are found in few publications. None of the references[2] studied show clearly defined variation

[1] A sedimentary variation series may be likened to a series of igneous rock types from the same rock mass which constitute the well-known igneous rock differentiation series.

[2] The following papers give some quantitative data on the texture of beach sands:

Udden, J. A., Mechanical composition of clastic sediments, *Geol. Soc. Am., Bull.*, vol. 25, pp. 667 and 703, 1914. For the most part the analyses are for scattered and unrelated samples.

Marshall, P., Beach gravels and sands, *Trans. New Zealand Inst.*, vol. 60, pp. 324-365, 1929. Gives the results of experimental work as well as textural study of beach gravels and sands of various beaches of New Zealand. The study is of related samples.

MacCarthy, G. R., Coastal sands of the east-

series as seen in the samples discussed in this paper.

THE GENERAL ENVIRONMENT

The map (fig. 1) shows the points from which the samples were collected

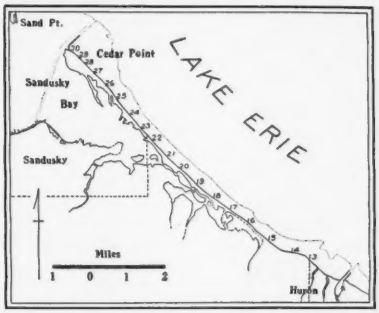

FIG. 1. Sketch map of Cedar Point, Ohio, showing the points of collection of beach materials. The numbers correspond to the numbers of the collected materials. Eighteen-foot subaqueous contour taken from Lake Survey chart.

and their relation to the shore line and shore features. The Cedar Point spit is built and is still being built across Sandusky Bay from east to west. Although the prevailing winds are from the west, the spit is growing in a westerly direction which, until the situation is more closely studied, seems to be abnormal. As can be seen by consulting a map of Lake Erie, the belt of islands extending from Marblehead peninsula, just west of Sandusky Bay, to Pelee Point on the Canadian shore, serves as a very effective wind and wave break. Thus, the waves generated by the prevailing winds have a fetch of but a few miles but the waves generated by the winds from the east and northeast have a fetch of the entire length of the lake from the eastern end to Sandusky Bay. Hence, even though the winds blow the greater part of the year from the west, the work done by the waves from the east with their fetch of about 200 miles is far greater than that done by the waves from the west with their fetch of about 20 miles.[3] As a result of the situation just described the rate at which the spit is being built is probably slow. The building of the spit westward is inoperative most of the year and the waves generated by the westerly winds carry back for some distance the material on the spit that they are competent to move.[4]

The spit and the beach are being built of material derived from four sources: (1) glacial till, (2) water-laid sediments of glacial lakes Warren, Whittlesey, and Maumee, (3) black Huron (Devonian) shale, the bed rock of the region, which is exposed with 1 and 2, at places along the shore east of the spit, and (4) subaqueous erosion of whatever material is on the lake bed and within the power of wave action, which may include 1, 2, and 3,

ern United States, *Am. Jour. Sci.*, vol. 22, pp. 35-50, 1931. A study of related samples.

Pettijohn, F. J., Petrography of the beach sands of southern Lake Michigan, *Jour. Geol.*, vol. 39, pp. 432-455, 1931. A study of both texture and mineralogy of related samples.

[3] D. W. Johnson has invoked a similar explanation for the spit at Toronto harbor on Lake Ontario. *Shore processes and shoreline development*, New York: John Wiley and Sons, pp. 97-101, 1919.

[4] It is understood, of course, that the littoral current developed by the waves is the actual agent of movement, but the movement by the littoral current is only active on particles placed in suspension by the incoming waves.

and possibly outcrops of rock other than the Huron shale.

SAMPLING AND LABORATORY TREATMENT

The writers are indebted to Miss Charlotte E. Webster of Elyria, Ohio, for the collection of the samples investigated and to the G. A. Boeckling Company, of Sandusky, Ohio, for permission to collect after the grounds had been closed to the public. Samples between a pint and a quart in size were collected at half-mile intervals all along the beach from a point about one mile east of the spit along the mainland shore to the end of the spit, a distance of about eight miles, except for the last sample which was only 700 feet from the preceding sample. Samples were taken to represent, in so far as possible, the average composition of the beach deposit by collecting the sand from the sides of a small pit located midway between the water's edge and the upper limit of wave action.

In the laboratory the samples were halved with a mechanical sample splitter until reduced to about 100 grams each. The weighed sample was then sieved dry as there was very little material smaller than 0.061 mm. in any of the samples. Each sample was sieved by hand through a set of sieves having the following diameters: 16 mm., 8 mm., 4 mm., and 2 mm. All the material passed through the smallest sieve was placed in a nest of screens having the following diameters: 1.4 mm., 1.0 mm., 0.71 mm., 0.50 mm., 0.35 mm., 0.25 mm., 0.177 mm., 0.125 mm., 0.088 mm., and 0.061 mm.[5] The sieves were shaken on a Ro-Tap mechanical shaker for a twenty-minute period. After the sieving the separated fractions were weighed and the percentage of the total sample represented by each was calculated. These percentages are given in Table I and represent the mechanical or textural composition. The individual separates were then treated with dilute hydrochloric acid to remove the acid-soluble material (mainly carbonate), filtered, washed, dried, and weighed. The per cent of carbonate in each size-grade and in the total sample was thus determined.

TEXTURAL COMPOSITION OF THE BEACH SANDS

Inspection of the histograms or distribution pyramids of the samples (fig. 2) and of Table I show definite changes from point to point as the sand moves along the beach and out on the spit. These changes are: (1) reduction in number of size-grades; (2) disappearance of secondary maxima; and (3) shifting in the position of the maximum or modal size-grade.

The samples in the upper half of the table (those from the mainland beach or nearest the mainland) show a great spread and measureable amounts

[5] From 2 mm. on down the scale for grading used is such that the *area* of a hole in any given screen is twice that of the area of a hole in the screen next below and half the area of a hole in the one next larger. This scale of grade sizes is more suitable for the study of these deposits than the Udden-Wentworth scale in which the diameters (and not the areas) stand in the geometric ratio of two. The latter grade scale gives entirely too few grade sizes to obtain a characteristic composition curve.

TABLE I. PER CENT BY WEIGHT OF SIZE-GRADES

Sample No.	Diameter of openings in millimeters												
	8–4	4–2	2–1.4	1.4–1	1–0.71	0.71–0.50	0.50–0.35	0.35–0.25	0.25–0.177	0.177–0.125	0.125–0.088	0.088–0.061	0.061–0.000
13	—	—	—	—	0.1	0.0	4.4	15.5	56.9	21.1	1.7	0.2	0.1
14	10.5	23.8	20.2	19.0	16.7	5.6	3.0	0.5	0.6	0.1	—	—	—
15	—	0.3	0.8	1.2	5.9	0.1	33.5	14.0	36.2	6.6	1.2	0.1	0.1
16	0.5	4.1	7.5	10.6	19.0	16.1	21.5	9.7	6.8	3.3	0.7	0.2	—
17	0.4	0.6	0.6	1.0	3.2	6.5	41.1	38.7	5.8	1.9	0.2	—	—
18	—	0.3	0.6	1.4	5.9	13.5	53.4	21.5	2.7	0.7	—	—	—
19	—	—	0.2	0.4	3.3	12.6	54.0	20.6	6.5	2.1	0.3	—	—
20	—	0.1	0.2	0.8	4.9	13.6	41.9	29.0	6.6	2.5	0.3	0.1	—
21	0.4	0.5	0.2	0.2	1.0	2.1	12.7	35.0	30.0	14.5	2.8	0.6	—
22	—	0.5	2.3	3.3	3.5	8.2	24.5	29.2	18.4	8.0	1.7	0.4	—
23	—	0.2	0.1	0.2	0.6	0.9	6.6	38.2	38.0	12.8	1.9	0.2	0.3
24	0.8	0.3	0.2	0.2	0.5	1.0	5.9	25.1	38.9	21.7	4.2	1.0	0.2
25	—	—	—	—	—	0.2	4.4	30.3	30.9	30.5	3.3	0.4	0.1
26	—	—	—	—	—	—	2.1	15.4	44.8	34.0	3.3	0.4	—
27	—	—	—	—	—	0.2	2.2	7.9	37.7	41.2	8.5	2.3	—
28	—	—	—	—	—	—	0.3	1.2	20.3	60.2	14.6	3.4	—
29	—	—	—	0.1	0.2	0.5	3.9	12.0	15.4	49.2	15.4	3.1	0.2
30	—	—	—	—	—	—	—	1.1	3.7	65.1	24.3	5.1	0.7

(greater than 0.1 per cent) usually occur in ten or more classes. Most of the samples from near the end of the spit and shown in the lower half of

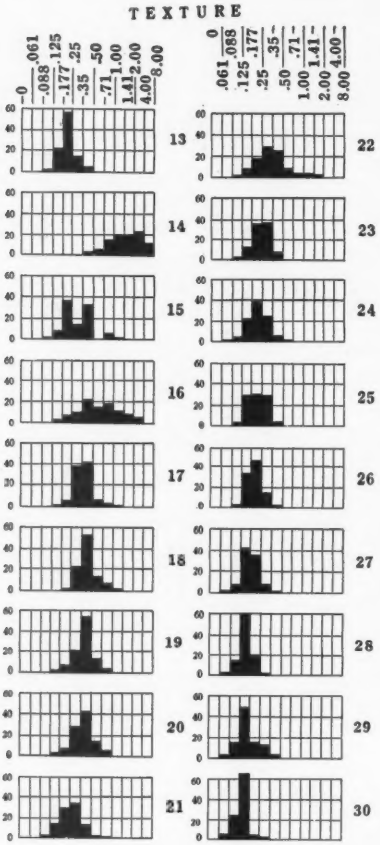

FIG. 2. Histograms of mechanical analysis of collected samples. The lengths of the vertical black bars are proportional to per cent of material between the indicated diameters (millimeters).

table have less than ten size-grades. For example, of the five samples 13-17, inclusive, only one has less than ten grades, but of the five samples 26-30, inclusive, four have less than ten grades. In general, however, the contraction in number of size-grades is not so marked as one might expect.

Secondary maxima[6] occur in the first four samples, 13 to 16 inclusive. The glacial lake sediments, into which the present lake is cutting, account in part for the abnormal character of samples 13 and 15 and the loading with the fine sand from the nearby cut cliffs results in the swelling of the percentages in the 0.250-0.177 mm. grade, the maximum in these samples. The normal grade for the beach sand in this vicinity appears to be the 0.50-0.35 mm. size, as shown by the high percentage in that size-grade in samples 15-20. That grade, however, has been reduced to a feeble maximum in sample 16, to a secondary maximum in sample 15, and to a very subordinate grade in samples 13 and 14 by the inclusion of an undue amount of fine material in samples 13 and 15 and by large admixtures of coarse material in samples 14 and 16. Samples 14 and 16 are exceptional in having an unusual amount of coarse material. It seems possible that the abnormal coarseness of sample 14 may be explained by assuming that it came, in the main, from a deposit of lag gravel at that particular locality. Samples 13, 15, and 16 show maxima in the coarse admixtures, the meaning of which is not clear. Sample 15 is most unique in having three maxima. In any case it is

[6] Maxima and secondary maxima are defined by J. A. Udden in Mechanical composition of clastic sediments, *Geol. Soc. Am., Bull.*, vol. 25, p. 658, 1914.

probable that the large secondary maxima such as have been described indicate an immature condition of sorting and that whatever their origin may be they normally disappear. Hence it is that none of the other samples analyzed show secondary maxima.[7]

The position of the maximum is the most significant feature of the entire set of beach sands. The maximum grade shows a clear and marked progression toward the finer sizes from sample to sample. One size-grade is dominant in a given sample, in the next sample the same grade contains a lower per cent than in the first while the next smaller grade has an increased per cent until what was the fine proximate admixture[8] has become the dominant or maximum grade and the former maximum has become the coarse proximate admixture. Thus in sample 16 the maximum is in the 0.50-0.35 mm. size-grade while in sample 21 it has shifted to the 0.35-0.25 mm. grade, while in sample 24 it has moved into the 0.250-0.177 mm. grade and it moves into the 0.177-0.125 mm. grade in sample 27 where it remains to the end of the series.

This migration of the maximum is associated with the changes undergone in percentage composition in each size grade as pointed out. Figure 3 shows

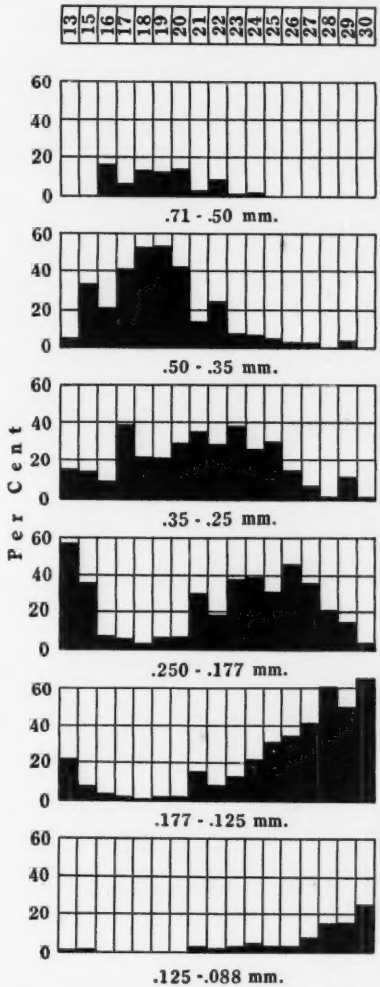

FIG. 3. Histograms of the principal size-grades. The vertical black bars are proportional to the per cent of the material in the size-grade designated in the various samples indicated by the numbers at the top of the diagram.

[7] The apparent small secondary maxima in samples 21, 23, and 24 in the coarse admixtures are of no importance. In all probability if the grade sizes in which they occur, 4-2 mm. and 8-4 mm., were divided to conform to the scheme of divisions used for the other size-grades, these maxima would disappear.

[8] Proximate admixtures refer to the size-grades next adjacent the maximum or chief ingredient. Fine proximate admixture refers to the next finest grade while coarse proximate admixture refers to the next coarsest grade.

the latter for the more important grades. The six grades represented in the diagrams show in graphic form the information to be obtained by a vertical reading of Table I in contrast to the graphic picture of a horizontal reading represented in Figure 2. Each

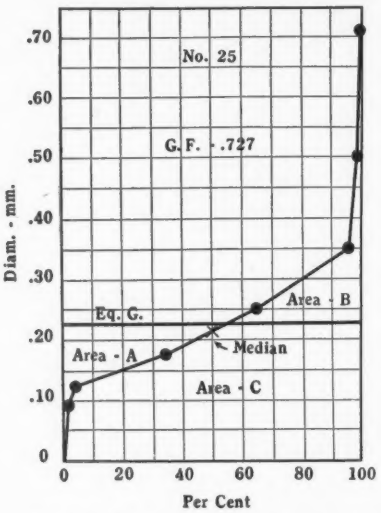

FIG. 4. Cumulative percentage curve illustrating the areas measured in computing the equivalent grade and grading factor of a sample. Also the median point on the curve.

of the four largest grades graphed rises in turn to a peak and then declines. The preliminary declines of grades 0.35-0.25 mm., 0.25-0.177 mm., and 0.177-0.125 mm. are due to the inclusion of a great deal of fine sand from the glacial lake deposits in these grades in samples 13-17, inclusive, which is rapidly washed out. These grades later rise and culminate in line with the general progression. This method of presentation shows the change in textures as related to the position of the sample in the series quite as well as do the histograms of Figure 2, but it is often necessary to consider the three principal grades (maximum, fine, and coarse admixtures) to realize that the progression toward finer sizes is actually going on.

There have been a number of attempts to represent the texture of a sediment with a single number. The most successful of these and the method least objectionable is that devised by Baker.[9] Baker used the *equivalent grade* as an expression of size and the *grading factor* as an expression of grading or sorting.[10] Since

[9] Baker, H. A., On the investigation of the mechanical constitution of loose arenaceous sediments by the method of elutriation with special reference to the Thanet Beds of the southern side of the London Basin, *Geol. Mag.*, vol. 57, pp. 366-370, 1920.

[10] For an abbreviated definition of equivalent grade and grading factor see Steiger, Geo., Field and laboratory studies of sediments, in W. H. Twenhofel, *Treatise on Sedimentation*, Baltimore: Williams and Wilkins, pp. 628-629, 1926.

Equivalent grade and grading factor constitute a pair of values unique for each and every sediment and are believed by the writers to be of great value both in the study of sediment variations and in classification of clastic sediments. They deserve much greater use than they have received to date.

Figure 4 shows their manner of derivation. TA is total area under the cumulative curve (Area B+Area C). This area is converted into a rectangle with the base of the diagram as one side. The length of the other side of the rectangle thus computed locates the equivalent grade, or that size equivalent to the sample in question if all of the sample were concentrated in but a single grade. VA is the sum of the two variation areas and is the total variation area (Area A+Area B). The grading factor is defined as:

$$\text{G. F.} = \frac{\text{TA} - \text{VA}}{\text{TA}}$$

In a perfectly graded sediment the grading factor is 1. The smaller the value for this figure the poorer the grading or sorting.

equivalent grade and grading factor are determined from the cumulative-percentage curve it was quite easy to determine the *median*[11] from the ogive curve as well as the other constants. Table II gives the values for these three figures.

TABLE II. THE MEDIAN, EQUIVALENT GRADE, AND GRADING FACTOR OF CEDAR POINT BEACH SANDS

Sample Number	Median (mm.)	Equivalent Grade (mm.)	Grading Factor
13	.210	.224	.788
14	1.520	2.058	.443
15	.292	.360	.578
16	.584	.806	.424
17	.362	.418	.681
18	.411	.464	.711
19	.393	.419	.835
20	.388	.424	.728
21	.256	.300	.618
22	.320	.414	.511
23	.242	.261	.733
24	.218	.264	.608
25	.211	.225	.727
26	.194	.206	.757
27	.174	.186	.739
28	.151	.156	.782
29	.157	.182	.675
30	.139	.140	.812

An inspection of this table shows at once that there is a marked and progressive decrease in size-grade as shown by the decline in the values for both the median and the equivalent grade. Minor fluctuations of either value may be attributed to the accidents of sampling. Figure 5 is a graph of the equivalent grade values for the samples against distance. The size decrease is evident. Variations in the value of the grading factor, which is a number expressing how near the sample approaches perfect sorting, are,

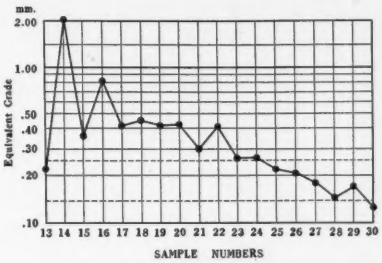

FIG. 5. Plot of equivalent grade against distance of travel. The numbers across the bottom are sample numbers spaced equally corresponding to the approximate half-mile intervals between points of collection.

however, more erratic and not nearly as systematic. In fact, little, if any, improvements in sorting beyond the first few exceptional samples can be noted. All samples are well graded excepting 14 and 16 which have the lowest values (indicative of the poorest sorting) of any of the sands studied. This means that the beach sands of this locality are as nearly perfectly graded as they will be under the existing conditions.

The above observations are summarized:

1. There is a progressive decrease in particle size as shown by (a) the decrease in value of the equivalent grade, (b) the decrease in value of the median, and (c) the shifting of the maximum grade towards the finer sizes.

2. There is no marked progression

[11] The median size is that size which divides the sample into two equal parts, one-half of which is larger than the median size and one-half is smaller. The median may be read directly from the cumulative percentage curve. It is to be remembered here that the median divides the sample into parts of equal *weight*. The median of statistics is generally the figure that divides the curve into parts each of which is equal in *number* of units.

in sorting as shown by the lack of trend in the values for the grading factor. A slight reduction in the number of size-grades indicates a little better sorting in so far as that reduction takes place.

3. Secondary maxima appear to be due to (a) loading by one of the four source materials (such as glacial lake sediments in samples 13 and 15)—in this case the secondary maximum is likely to occur always at some definite place in the grade scale; (b) inclusion of lag concentrates in the samples (as in samples 14 and 16)—in this case the secondary maximum will occur in the coarse admixtures at no definite place.

4. The various sources of supply are represented by secondary maxima in some cases or by abnormal swelling in the percentage in other grades (even though these never attain the importance of maxima) if the sample is taken near the point of supply of the source material concerned.

THE CARBONATE CONTENT

The carbonate appears to be detrital, that is, grains of calcite or dolomite derived from the glacial deposits or from shells and shell fragments. Two things are of interest in regard to the carbonate, namely, the total quantity of carbonate in any sample and the amount of carbonate present in each size-grade.

The total quantity of carbonate in any sample is small. Sample 14 has the most carbonate, namely 12 per cent. The most of the samples have between 2 and 3 per cent. There is progressive change in carbonate content through the series though this progression is not always regular nor is it very great. The carbonate declines from an average of 7.4 per cent in the first four samples (13-16) to a minimum of 1.94 per cent in sample 23 and then rises to 4.86 per cent in sample 30.

The per cent of carbonate in each size-grade was also studied and it is

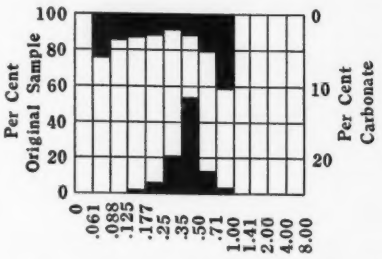

FIG. 6. Diagram showing the per cent of carbonate in the different size-grades of sample 19. Normal histogram in lower part of figure. Inverted histogram of carbonate per cent at top of diagram.

to be observed from Table III that the carbonate constitutes a larger per cent of the finer and the coarser grades than it does the intermediate grades. In fact, there is actually a greater quantity of carbonate in the intermediate grades but the percentage is smaller. The sizes 0.25 to 0.5 mm. have in nearly all cases the least carbonate percentages. These relations explain the total carbonate percentage referred to in the paragraph above. Those samples whose maximum occurs within the 0.25-0.5 mm. range show a minimum of total carbonate and those samples whose maximum is coarser

or finer (samples 13-16 and samples 28-30) have a greater quantity of carbonate.

Figure 6 shows graphically the relations for a single sample which will serve as an illustration. In this figure the analysis of the original sample (including carbonate) is plotted in the normal position and just above this histogram is plotted the per cent of carbonate in the various grades in an inverted position. The more or less reciprocal relations are thus well shown. A similar figure would result from the plotting of the data for the average of the eighteen samples analyzed showing that this relationship is fundamental and peculiar to any one sample or the average of the group.

In summary it may be said that carbonate, detrital in origin, is present in all samples in small amounts and appears to be least in samples of intermediate texture and greatest in samples of very coarse or very fine composition. Furthermore, the carbonate is present in largest quantities in the same size-grades which show the largest quantity of non-carbonate material but it is present in *relatively* greater quantity in the finer and the coarser grades, that is, the per cent of carbonate in a size-grade is larger in the extreme size-grades.

DISCUSSION

It is difficult and often misleading to attempt an explanation of the variations in character of a series of collected sediments because there are so many factors in the environment that must be taken into account. This is due partly to lack of knowledge of the factors and of quantitative data concerning them and partly to the complex interaction of the factors on each other and on the sediment.

A sedimentary deposit is a product of a certain environment in which the sediment is stable. A variation in composition of the sediments as collected in different places is therefore the result of variations in some factors in the environment. It is not easy to discover, however, just which factor or factors may be responsible for any particular variation. Consequently the following statements in regard to the Lake Erie beach deposits are suggestive rather than final.

The variation in size, that is, the decrease in average size-grade during transportation of the materials along the shore, is perhaps the most important variation. The cause of this change would appear to be one of several, namely, either a size reduction due to abrasion, or a selective process instituted by the littoral current together with the undertow and waves, or to an adjustment between the textural composition and some factor in the environment which varies regularly from point to point. The size reduction by abrasion is quite unlikely for the particular case in question. Anderson[12] has shown experimentally that rounding of grains by abrasion is a much slower process than generally supposed. Reduction by abrasion is further disproven by the lack of appreciable rounding of the grains near the end of the spit structure where

[12] Anderson, G. E., Experiments on the rate of wear of sand grains, *Jour. Geol.*, vol. 34, pp. 144-158, 1926.

TABLE III. THE PER CENT OF CARBONATE IN EACH SIZE-GRADE[a]

Sample No.	Diameter of Openings in Millimeters												
	8–4	4–2	2–1.4	1.4–1	1–0.71	0.71–0.5	0.5–0.35	0.35–0.25	0.25–0.177	0.177–0.125	0.125–0.088	0.088–0.061	0.061–0.000
13	—	—	—	—	(22.4)	(0.0)	8.0	4.8	5.9	8.3	8.2	(16.3)	—
14	8.1	14.0	14.0	12.7	9.8	7.7	8.1	(6.9)	(8.2)	—	—	—	—
15	—	—	(12.2)	12.1	8.2	(4.5)	4.7	5.0	5.7	6.8	19.9	—	—
16	(20.6)	9.5	10.6	9.5	5.6	3.3	3.2	2.8	2.9	5.6	(23.0)	(47.0)	—
17	—	(0.7)	(11.2)	8.1	5.1	2.7	1.9	2.2	2.6	4.0	(4.8)	—	—
18	—	(29.1)	(8.7)	8.8	4.9	2.5	3.3	2.3	2.4	(2.8)	—	—	—
19	—	—	(18.1)	(10.7)	5.1	2.6	2.0	2.6	3.1	3.6	(6.0)	—	—
20	—	(14.1)	(20.0)	7.7	5.0	2.6	1.7	2.8	2.7	3.7	(5.5)	—	—
21	—	(8.7)	(3.3)	(3.6)	5.8	2.4	1.6	2.0	2.0	3.3	4.5	(7.1)	—
22	—	(16.2)	7.3	5.6	4.3	2.4	1.6	1.8	2.1	3.7	6.1	(6.0)	—
23	—	(3.3)	(1.3)	(0.9)	(4.1)	2.5	1.9	1.5	1.9	2.1	6.9	(6.3)	—
24	(1.6)	(10.3)	(13.5)	(3.2)	(4.7)	2.6	2.1	2.1	2.0	3.6	7.1	6.0	—
25	—	—	—	—	—	(4.5)	2.3	1.8	0.5	3.0	7.1	(9.0)	—
26	—	—	—	—	—	—	1.8	1.8	2.1	3.1	7.3	(8.0)	—
27	—	—	—	—	—	(2.0)	2.0	1.7	2.0	3.2	6.4	6.6	—
28	—	—	—	—	—	—	(3.0)	2.6	2.3	3.2	6.0	7.4	—
29	—	—	—	(10.3)	(4.7)	(2.6)	2.7	1.6	1.7	2.8	5.5	7.9	—
30	—	—	—	—	—	—	—	6.7	4.2	3.9	6.1	10.1	(21.5)

[a] The percentages enclosed in parentheses are those which have been calculated from amounts of less than 1.0 gr. of original material. It is to be questioned if the results from amounts of less than 1.0 gr. of original material can be considered to be very reliable.

certainly a high degree of rounding should be exhibited if these grains represent the abraded residuum of the coarser sand nearer the mainland. Appreciable abrasion is therefore ruled out. Marshall concluded that abrasion takes place with extreme slowness when a beach is composed of material finer than 3.4 mm. in diameter. Marshall,[13] however, ascribes the absence of coarse grades to the "relatively rapid abrasion of those grades; the absence of finer grades to the flotation of these grains and their removal seaward by the backwash."

A second hypothesis to account for the decrease in size is that of selection by the waves and littoral currents that would result in a separation of the original material supplied to the beach into a series of graded fractions and result in the deposition of these fractions in order from the mainland to the end of the spit. The beach sands are transported by littoral currents only after these materials have been put in suspension by the waves and undertow. The distance any given particle moves depends on how often and how long that particle is in suspension. For any given set of conditions some material will be too coarse to be moved at all and will therefore remain in one place, constituting the lag gravel. There is thus an upper size limit to the material which is transported. For any given set of conditions there is also a certain lower limit. This lower limit is the size above which the materials are shifted landward during the interplay of incoming waves and the outgoing undertow and below which the material is carried lakeward at the same time. There is thus a range of size limited upward and limited downward which can be transported parallel to the shore in the beach zone. This is the shore drift and the material is mainly sand. Conditions of wave and current strength are not uniform and as a result the limiting sizes vary somewhat. Consequently there are times when certain particular sizes near the upper grade limit may not be shifted along the beach at all. And since the distance a particle moves depends on how often and how long that particle is in suspension, it is evident that the particles of smaller size, near the lower limit of the sizes shifted parallel to the shore, will travel the greatest distance in the long run. As a result there will be a tendency for the sizes transported to be separated with the finer materials outrunning the larger sizes and traveling all the way to the end of the spit, leaving the coarser sizes at intermediate points with the very coarsest material but a little distance, if any, from the points of origin, the wave-eroded shore further east.[14] At any given point along the shore there will be a certain dominant size, a little oversize, and a quantity of undersize. It would seem, however, that if the coarser material is moved at all, such material would ultimately reach to the end of the spit

[13] Marshall, P., *op. cit.*, pp. 344 and 355.

[14] MacCarthy, G. R. Coastal sands of the eastern United States, *Am. Jour. Sci.*, vol. 22, p. 37, 1931. MacCarthy assumes the decrease in fineness of beach sand to be due "not only to a wearing out of the finer material, but also to the faster movement of the finer material, so that the coarser portion has a tendency to lag behind." See also Johnson, D. W., *Shore processes and shoreline development*, p. 96.

and therefore the texture of the beach materials ought to be much the same all along. If it is not there in the same proportions, therefore, there must be some other factor operating in the particular case.

Such a factor in the environment which varied regularly from place to place was sought. The shoreline is nearly straight and maintains about the same orientation to the prevailing winds[15] or effective wave fetch. The offshore slope appears less steep near the end of the spit than at the points of wave erosion on the mainland as shown by the Lake Survey charts showing depth figures. This change in the subaqueous profile does not appear very marked nor uniformly progressive enough to account for the observed textural changes. It may, however, be a factor of importance. An overflat subaqueous profile might result in enfeebled wave action on the subærial part of the beach from which the samples were taken, the supposition being that the greater part of the wave energy would have been expended over the wide zone of shallow water. Where deeper water prevails offshore, most of the wave force is expended on a narrow zone near the shoreline. It appears to be generally true that shores where wave action is feeble are characterized by finer deposits than those which are subject to vigorous wave attack. Marshall[16] shows by tabulated mechanical analyses of beach sands from exposed beaches and from sheltered beaches that there is a consistent difference, namely, the more exposed the beach the coarser the sand, or conversely, the finer the sand the more sheltered the beach. One may call to support this generalization the fact that gravel beaches mark headlands and promontories and sands are found at the heads of bays.[17] Sufficient data are not at hand to establish the truth of the case for the particular deposits studied.

Marshall[18] quotes Cornish on the relation between size-grade and slope of the beach, noting that beaches with coarse material are generally steeper than those with finer material. Marshall, however, ascribes this slope of the beach to the size of the material, whereas Cornish believed that the size of the material on the beach was determined by the slope.

The variation in carbonate has been discussed and explained in terms of the per cent of carbonate in the different size-grades. It remains to be explained why the carbonate is in greater proportion in the largest and the finest sizes and less in the intermediate grades. This seems to be true of many sediments investigated in the laboratories at Chicago, even glacial till. No satisfactory explanation has so far been discovered. Unpublished data show that this relationship is present but less marked in outwash sands than in lake beach deposits.

[15] The orientation of shore to the effective wave fetch was invoked to account for the variations in composition of the Lake Michigan beach sands. See Pettijohn, F. J., Petrography of the beach sands of southern Lake Michigan, *Jour. Geol.*, vol. 39, pp. 432-455, 1931.

[16] Marshall, P., *op. cit.*, pp. 353-356.

[17] This appears to explain also the marked difference in texture of the beach sands on the two sides of Lake Michigan. See Pettijohn, F. J., *op. cit.*, p. 453.

[18] Marshall P., *op. cit.*, pp. 363-365.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 2, NO. 2, PP. 89-124, FIGS. 1-15,
AUGUST, 1932

A HISTORY OF THE PRINCIPLES AND METHODS OF MECHANICAL ANALYSIS

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ABSTRACT

Decantation methods for separating particles extend back to ancient Greece, but no applications were made to soils or sediments until 1692. Sieves were used to separate sands in 1704. The need of understanding the composition of earths for classification was recognized in 1750. The earliest recovery of three grades by sedimentation occurred in 1784. The term "mechanical analysis" was introduced in 1800. Sieving and decantation were combined into a single technique in 1805. The first rising current elutriator was used in 1839. In 1851 Stokes' law was formulated; in 1867 it was applied to mechanical analysis. The earliest use of graphs to represent sediments was made in 1892. In the same year the centrifuge was applied to mechanical analysis. Air analyzers were introduced in 1906. In 1912 simple sedimentation cylinders reached an apex in their development. In 1915 the continuous sedimentation balance appeared, and a mathematical theory of sedimenting systems was developed. The first manometric tube was introduced in 1918. The pipette method was developed in 1922, and the hydrometer method in 1927.

INTRODUCTION

Current interest in mechanical analysis has moved the writer to endeavor to trace the history of the techniques used, with particular reference to the principles and apparatus involved. Certain attendant questions, such as the preliminary dispersion of samples, the development of grade-scales, and the presentation of data, are briefly discussed. No particular attention is paid to mineralogical analysis or to shapes or roundness of grains; indeed, what extraneous material is touched upon is subordinated to the main theme. Two main purposes have been kept in mind in the development of the paper: to review the history of the principles and methods, and to furnish a bibliography to aid contemporary workers in finding techniques best adapted to their particular problems.

Source materials for a history of the subject are widely scattered and often difficult to find. Historical treatments of pedology, particularly those of Neuss (99)[1] and Giesecke (49), have disclosed many valuable leads to the earlier literature. Unfortunately, numerous references were by name only, which necessitated considerable search before the particular papers or volumes could be found. The present writer has therefore determined to cite all literature fully, and to indicate by asterisks all references not personally seen.

Compilations confined to the pedological aspects of the subject did not constitute the sole guide to the literature. Bibliographies and discussions covering some of the more recent de-

[1] The numbers in parentheses refer to the bibliography arranged at the end of this paper.

velopments in mechanical analysis were found in papers by Odén (104), Wetzel (176), Köhn (77), Rubey (122), and Roller (120). Von Hahn's *Dispersoidanalyse* (52), and Gessner's *Schlämmanalyse* (48) have also been of considerable aid. Much valuable material was found in the works of the eighteenth century mineralogists, among whom Wallerius (169) is particularly to be mentioned. Linné (84) included a comprehensive "Verzeichniss aller mineralogischen Schriften" among his volumes, and Boehmer (13) furnished another excellent source of early writings. Some of these references will also prove of value for historical treatments of other aspects of sediments.

An exhaustive historical treatment could not be secured without a much more detailed analysis of the literature, and this review should be considered at best as an attempt to sketch only the major developments of the science. The writer would appreciate advices concerning omissions of consequence.

EARLY PERIOD

Mechanical analysis, requiring an experimental technique, waited for its development upon the growth of experimental science in general. Accordingly, it may be expected that previous to the eighteenth century very few if any quantitative studies had been made, but a body of qualitative knowledge certainly was available from which to draw when the quantitative aspects assumed their due importance. Among these qualitative notions we find references to the differential rates of settling of particles in water, although it waited for Stokes at a much later date to give a quantitative mathematical expression to this phenomenon.

The earliest reference to the process of mechanical analysis was found by Jarilow (66) among the works attributed to Hippocrates (*ca.* 400 B.C.), but generally recognized to be the work of some unknown contemporary. Here was a clear though implied understanding of differential velocities of settling, and even a description of an apparatus which could be used to demonstrate the principle. The apparatus consisted of a tube, attached to a bladder, into which earth, sand, and lead-powder were to be thrown. If water were poured into the bladder, said the writer, the various substances would at first mix with it, but shortly would settle down, each to itself.

In addition to this theoretical discussion of the subject, the ancients actually applied the principle of decantation to the purification of earths, as may be learned from Theophrastus (153, pp. 137 ff.):

> It is only a Sand, shining like Scarlet, which they collect, and rub to a very fine Powder, in vessels of Stone only; and afterwards wash in other Vessels of Brass, or sometimes of Wood: what subsides they go to work on again, rubbing it and washing it as before. And in this work there is much Art to be used; for from an equal Quantity of the Sand some will make a large Quantity of the Powder, and others very little, or none at all. The washing they use is very light and superficial, and they wet it every time separately and carefully. That which at last subsides is the Cinnabar, and that which swims above in much larger Quantity is only the superfluous matter of the washing.

The beginnings of our present practices, we thus observe, must be sought among the writings of the early Greeks and possibly the Romans, and we may expect that further research will disclose additional items similar to that of Theophrastus.

From the time of the ancient Greeks until near the beginning of the eighteenth century, no material on the subject was found in the several works available to the writer. Staudacher (143, pp. 72 ff.), indeed, particularly mentioned that the Roman literature is quite barren on the subject of soil analysis.

When experimentation on soils and earths began, it was a common practice to subject them successively to water and various acids and fluxes, to determine their several properties. It is not surprising, therefore, that we should find references to their behavior in water at a comparatively early date. König (78, pp. 181 ff.) pointed out as early as 1686 that a certain red earth, when diluted with water, diffused a red color through it: "RUBRICA FABRILIS *rubicunda est, spissa, gravis, quae aqua diluta velut sanguineum colorem diffundit,*" and he recognized that clay is unquestionably composed of very fine particles: "ARGILLA *massa est terrea, . . . constat nimirum ex particulis terreis minoribus. . . .*"

In 1684 Lister (85) published a classification of sands and clays, and from the text of his paper it would seem that he was acquainted with the behavior of sands in water. In his classification appears Calice sand, of which he said, "[it] burns reddish, but falls not in water." The following excerpt of his discussion on clays is interesting:

> Also I here give a scheme of Clays, . . . as because the mixture of *Sand* and *Clay* is not unusually called Earth. Yet this terme being too large it will be convenient, as I think, to limit it to such a mixture as we usually find upon the surface of the ground, which hath ever in it, besides such *Sands* and *Clays*, . . . a great part of the rotten parts of *Plants* and *Animals*.

The earliest reported case of a mechanical analysis was found by Keen (70, p. 9), who quoted an account of the analysis made by Houghton, which he found in a later work by Mortimer (93). From the references given, the writer was able to locate an original account of the experiment. It occurs in a later reprint (63, vol. 1, pp. 25 ff.) of Houghton's work, and is dated 1692. Because of the uniqueness of this first analysis, it is quoted in full below:

> Num. IX, Saturday, May 7, 1692: *The history of* clay; sand *must be in due proportion. The history of* fullers-earth; *no* sand *in it, therefore fit to cleanse* cloth.
>
> The history of clay I promis'd in my last runs thus, I took a piece of *clay* from a load that was provided to lie under the floor of a stable, to hinder the moisture running into a cellar; I ask'd the workmen if it was such *clay* the brewers used to stop their barrels with, which was affirmed. This *clay* weighed *four ounces and an half* averdupois. I dissolv'd it in water, pouring off the (*turbid*) thick water, till all was gone but *sand*, which stuck not together, but lay loose in the water, and when 'twas dry 'twould run as usually we see other sand do, and, I suppose, is the nature of all *sand*. I had *one ounce* of this *sand* of a *clayish colour, fineness* much like that in hour glasses, with some little *glistering*, and some little stones and other fowl matter

with it. When the *clay* was settled, I poured off the water, and left the rest to dry in a pewter-bason, and when it was so, it crackt, and the pieces, with *sand*, as above described, I have by me.

I also took *four ounces and a half* of *fullers-earth* in one piece, 'twas like a soft stone, which, when put in water, did not easily dissolve without rubbing, but by much of that its parts did separate. I (*decanted*) pour'd off the thinnest, and at the bottom was above a quarter part of a heavy thick substance, that when separated would fall so again. I dry'd both the settlements asunder, the first was a pure *bright colour*, and did stick together, but it was very (fryable) easie to be broke into powder, which was so *fine*, that it seem'd to be lost in the pores by rubbing it between my fingers and thumb; the other will not rub so fine, but yet feels *soft*, so that in neither can I find the least *grain* of *sand* or *gravel;* I also lookt in my (*microscope*) magnifying-glass, and both sorts of this earth were (opaque) not to be seen through, nor glistering like *sand;* . . .

THE EIGHTEENTH CENTURY

The separation effected by Houghton depended entirely upon a process of sedimentation, and it is quite appropriate that the earliest use of sieves as instruments of size-grading should also have occurred at about this time. In 1704 Van Leeuwenhoek examined several sands and rocks with his recently developed microscope, and in commenting on the shapes of the grains, he said (163, pp. 1538 ff.):

When I viewed several grains of the abovesaid Sand with my microscope, I was surpriz'd to see that many of them were hexangular, and the more, when I had sifted the finest from the coursest; neither could I observe that any of the Sands were like each other.

Sieves were actually used earlier than this in other lines of work; for instance, in 1671 mention is made of "an hairen sieve, through which we sift," in an article on the mining of tinstone at Cornwall (3). Van Leeuwenhoek, however, appears to have been the first to use sieves for the scientific investigation of sediments.

Modern workers who have been faced with the problem of disaggregating indurated rocks will be interested in Van Leeuwenhoek's solution of the difficulty:

That piece of the Red Stone that still remain'd entire was about the bigness of a Pea, and when I beat it in pieces, there flew a Spark of Fire out of it.

Peter Shaw delivered a series of lectures on chemistry in 1731-32, and included an account of his analysis of garden mould (139, pp. 60 ff.):

We washed the remaining terrestrial Matter in several Waters, every time decanting the upper muddy Liquor, after a little standing, in order to procure the pure Sand contained in the mould; and found the Sand to be a large proportion of the whole.

In 1746 John Hill (153, pp. 114 ff.) discussed earths in some detail. From his descriptions we may borrow two:

1. *Clays* are Earths composed of very fine Parts, smooth, heavy, not easily mixing with Water; and when mixed, not readily subsiding in it; . . . 5. *Chalks* are earthy Substances, dense, brittle, readily diffusible in Water, and quickly separating themselves from it by Subsidence. . . .

In 1750 Wallerius clearly indicated a knowledge of the ability of water to disperse some earths and not others. He emphasized that earths (among which he included soils, clays, and sands) are mixed with various other substances, and that to distinguish

among them, it is necessary to observe how earth and sand are mixed together. This first clear statement of the principle deserves to be quoted (169, p. 6, footnote):

> . . . denn alle Erde, die wir finden, ist mit verschiedenen steinartigen, saltzartigen, verbrennlichen oder schwefelichten, und metallischen Teilen vermenget, wovon ein grosser unterscheid unter den verschiedenen Erdarten herrühret: wie denn auch Erde und Sand eins in ein andere vermischt sind; so müssen wir die Erdarten, so wie wir solche finden, betrachten, das ist, in ihrer Zusammensetzung, und mit ihrer Vermischung, und nach dieser Masgebung den Unterscheid unter denselben vorstellen.

After this introduction he described the properties of the earths, and among his remarks are to be found numerous references to the behavior of sands and clays in water. One of the most interesting is his description of a method of separating the mica from micaceous sand by sedimentation (169, pp. 49 ff.). He directed that any mixed earth should be washed out, the clean sand placed in another vessel with clear water, and thoroughly stirred. When the vessel is set at rest, the sand settles to the bottom more rapidly than the mica, so that two layers are formed. These layers are to be removed separately and dried. The mica may then be freed of any remaining sand by allowing it to fall on an inclined sheet of paper. The mica flakes adhere to the paper, and the sand grains roll off.

According to Neuss (99, p. 459), Wallerius also recognized the value of soil analysis, and his work on agriculture (170) may well repay search for possible methods of analysis.

In 1769 Eller (39, p. 251) used sedimentation to observe earths in greater detail, by stirring them in water. He noted that the sand settled first, and the finer components formed thin layers above it.

In 1774 Schröter's important volume on rocks appeared, in which (131, pt. 2, p. 235) appeared the first mention of the process of mechanical analysis as *zu schlemmen,* which may be translated as "decantation" or "sedimentation" as currently used in mechanical analysis. His use of the term follows:

> Wenn man den Speckstein klein stösset, und schlemmet, so lässt er sich doch einigermassen auf den Scheibe drehen. . . .

It is to be noted that Schröter implied the process of *schlemmen* to be so well known, that he need not even describe it.

In 1777 appeared Linné's *Natursystem des Mineralreichs,* a German translation of the 12th Latin edition. In discussing material that may be mixed with clay, he said (84, pt. 4, 1779, pp. 345 ff.) that in order to determine their relations more precisely, one should *schlemm* a given quantity of the clay in the regular way (*auf die gewöhnliche Art*) until all the lighter particles have gone over, and only the heavier remain behind. The turbid water is then allowed to stand until the clay has settled, and by drying and weighing the deposit, one may learn how much sand is in the clay.

In 1784 Wiegleb (178) published an account of his analysis of gneiss from Freiberg. He crushed the rock in a mortar and after treating it with acids, he stirred the residue with water in a

glass. He noted that a coarse sand settled to the bottom, while a lighter white powder remained in suspension. He separated the fractions by decantation and dried and weighed them.

The year 1784 is also marked by the publication of De Beunie's researches on soils (34). He took three pounds of earth and washed it twelve times, in each instance pouring the turbid water into a second vessel, and finally into a third, so that he obtained three earths. The first was coarse, the next somewhat finer, and the third was extremely fine. He described the characteristics of each of the fractions, and mentioned the use of a lens in examining them. Each product was weighed, and the results set out in a neat table, with even an evaluation of the error.

In discussing the three grades, De Beunie mentioned that the first settled very soon, the second at the end of six hours, and the third only after twenty-four hours, and even so the water still remained turbid. De Beunie thus recognized that the rate of settling was a function of the time, but he failed to mention that the height of the column of water was also involved. On the whole his analyses marked a distinct step forward, because they were the first attempts to obtain more than two grades by the method.

In the same issue of Crell's *Annalen*, Storr (146) mentioned the sedimenting of clay to separate the sand from it.

Rückert published his work on agriculture in 1789-90, and in it (123, vol. 1, pp. 58 ff.) he described his method of analysis. The process was mainly chemical, but one item of interest was that he removed the larger stones from his samples before mechanically analyzing them.

In 1795, according to Giesecke (49, pp. 47, 49), the Earl of Dundonald (Archibald Cochrane) (24) carried out researches on the mechanical composition of soils, but no details were furnished by Giesecke. In the year following, Kirwan (72, pp. 71, ff.) published a method of analyzing soils, and removed all stones above the size of a pippin before running the analysis. On page 59 he discussed a silicious sand mentioned by Bergman, and pointed out that as Bergman himself said (12), it is really a gravel, consisting of stones from the size of a pea to that of a nut. We may gather from this and other remarks, that the notion of limits to size-grades was beginning to develop, although no very definite sizes were yet recognized.

Thaer described a method of mechanical analysis in 1798 (151, vol. 1, pp. 101 ff.). He dried his samples, and picked out all stones larger than a hazelnut. The gravel-free soil was boiled for a half-hour and passed through a sieve to determine the amount of vegetable fibre present. The earth was dried again, treated with acid to remove the carbonates, and the insoluble residue separated into sand and clay by sedimentation. He repeated the process until the water remained clear, and determined the clay by difference.

THE NINETEENTH CENTURY

The term "mechanical analysis" was introduced to the literature in the first

year of the nineteenth century, as far as the writer has been able to trace it. In 1800 Fleuriau-Bellevue (43) defined mechanical analysis as a sort of anatomy of rocks, consisting of trituration, followed by washing, and an examination of the resulting products. He clearly recognized the value of mechanical analysis to geology as a means of discovering new minerals and of learning the nature of rocks:

> Je croirois donc que des analyses mécaniques . . . seroient un puissant moyen de découvrir de nouveaux minéraux, de connoître la nature des roches et de hâter ainsi les progrès de la géologie.

Several advances in the principles of mechanical analysis were also made in the early years of the century. Chief among these was the method of soil analysis proposed by Davy (32) in 1805. In his pamphlet he described a method both chemical and mechanical in nature. The apparatus he used included a wire sieve "sufficiently coarse to admit a pepper corn through its apertures," which was used to remove the larger particles from the soil. Thaer had used a coarse sieve to remove the vegetable fibres from his boiled samples, but apparently he did not use it to separate the pebbles.

Davy dispersed his samples by shaking them in water; the vessel was then allowed to stand a few minutes, so the sand could settle. The turbid liquid was decanted, and the fine material filtered off.

After the soil had been divided into fractions, the carbonates were removed and a series of chemical tests followed. Davy departed from Thaer in the treatment of the carbonates, removing none of it before his mechanical analysis.

According to both Neuss (99, p. 463) and Giesecke (49, p. 54), the earliest true mechanical analysis was made in 1804 by Cadet de Vaux (20), but no details were furnished. The book was not available to the writer.

According to Cadet de Gassicourt (19), Rozier (121) published a method of analysis in 1809 which was patterned after that of Davy.

The American edition of Davy's *Elements of agricultural chemistry* appeared in 1815, and in it he dispersed his samples by boiling them in water (33, p. 140). Davy was the first to subject his samples to this treatment. Neuss maintained that Davy used sieves with various meshes,[2] but the writer was unable to verify that more than a single sieve was used in any given analysis.

In 1816 Cordier (25) separated crushed rock fragments by sedimentation to prepare them for microscopic study.

The second edition of Thaer's *Grundsätze* appeared in 1821, and in it he classified sands into three sizes, termed "Quellsand," "Perlsand," and "Flugsand," although he gave no dimensions (152, vol. 1, pt. 3, p. 52). As to sand in general, he said it should include only the part that settled to the bottom during an analysis, but not the much finer "Kieselerde" which was mixed with the decanted clay (152, vol. 1, pt. 3, p. 100). This finer component, he said (152, vol. 1, pt. 3, pp.

[2] (99), p. 467: "Er verwendet hierzu Siebe mit verschiedenen Lochweiten."

58 ff.), could be freed from the clay by boiling the decanted portion until the "Kieselerde" separated out.

Other workers who published methods of analysis patterned after Davy or Thaer during this time were Chaptal (22), Sprengel (141), and Culen. The last was cited by Neuss (99, p. 463), but no reference was given.

In 1830 Schübler's *Grundsätze der Agricultur-Chemie* (132) appeared. This was the most important work of the first half of the century, because of the wealth of material contributed. Schübler is recognized as the father of soil physics, and his title is well justified. Although he used a method of soil analysis not much advanced beyond that of his contemporaries, he nevertheless anticipated the principle upon which the later hydrometer method is based. He established the first grade-sizes in terms of actual dimensions, and he appears to have been the first to express the results of his analyses in percentages.

Schübler dried his soil and removed the pebbles with a sieve having meshes of ½ Linie[3]: the first specification of sieves in terms of actual arithmetical units. About 500 grains of the sieved soil were then separated into sand and clay by repeated sedimenting, and he mentioned Thaer's method of boiling the decanted fraction to obtain the fine sand from the clay as a third grade.

After the mechanical analysis was completed, the grades were tested for carbonates and other chemical constituents. In this respect Schübler followed Davy. He differed from his contemporaries in converting his results into percentages.

Although Schübler specified only one sieve in the description of his method, he pointed out elsewhere (132, pt. 2, pp. 6 ff.) that sand could be divided into several sizes by means of sieves. His grade scale extended from "Perlsand" (1 Linie diameter), through "Grober Sand" (½ Linie), and "Feinsand" (¼ Linie), to "Flugsand" (1/10 Linie). It is interesting to note that the first three sizes were in the ratio n, $n/2$, $n/4$, as they are today.

The most interesting part of Schübler's volume is his intelligent discussion of suspensions, and his clear understanding of the increase in specific gravity of a liquid due to solid particles suspended in it. He observed that when clay was added to water, the specific gravity of the suspension was first increased, and then gradually decreased as the clay settled. Indeed, he even prepared a suspension, and determined its specific gravity with a hydrometer (Aräometer) at short intervals, to study the changes that took place as the clay settled. He found in his particular suspension that the specific gravity dropped from 1.046 to 1.002 in a period of forty minutes. He failed to point out the significance of these facts to mechanical analysis, but the principle at least was established.

A contribution to the preliminary treatment of samples was made in 1830 by Hundeshagen (64, pp. 64 ff.), who mentioned that clay could be separated from the coarser material by sedimentation, especially after boiling in water, or in a dilute solution of

[3] One Linie is approximately 2 mm.

alkali (to remove the humus), or in dilute acid (to remove the carbonates). This suggests that he recognized the necessity of treating samples on the basis of their particular natures. Another remark of his is interesting in its bearing on flocculation. He recognized that suspensions of clay could be precipitated by the addition of small amounts of potash or alum.

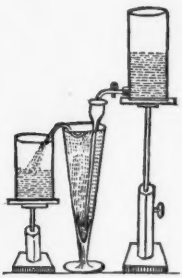

FIG. 1. Schulze's Elutriator. (Reproduced from *Jour. für praktische Chemie*, vol. 16. p. 505, 1839.)

The first apparatus for mechanical analysis was developed by Franz Schulze (133) in 1839. It is reproduced in Figure 1, and it consisted of a "champagne-glass" into which a thistle tube was introduced. He sieved the pebbles from his samples, and boiled the fine material for 10 minutes. The boiled sample was poured into the glass, and a current of water from a reservoir sent through the tube until it remained clear. The rising current carried off the fine material, and left the sand behind. Schulze recognized the necessity of controlling the strength of the current.

An important essay on mechanical analysis was written in 1840 by Rham (113), in which for the first time a nest of three sieves was used in conjunction with decantation. Grit and two grades of sand were obtained by sieving, and the fine material was separated into three more fractions by decantation. Rham also described the first volumetric settling tube, which he specified should be three feet long and three-fourths of an inch in diameter. It was filled half-full of water, and a sample of the soil was stirred in a separate vessel with about an equal volume of water. The suspension was poured into the tube, and allowed to stand upright. After a half-hour the sedimented material was measured with a scale, and the proportions of the sizes determined.

The earliest use of the word "elutriation" was found in a paper by Fownes (44), published in 1843. He referred to Davy's decantation method, and said, "It is . . . carefully elutriated with distilled water." Thus in its introduction, the term was not confined to separation by rising currents of water.

In 1843 Gasparin's *Cours d'agriculture* (47) appeared. In it he described a method of analysis involving the separation of three grades by sedimentation. The grains above 1.5 mm. were sieved off, and the fine material stirred with water. The turbid liquid was decanted while still in motion, and the process repeated until the water was clear. A coarse sand remained, which he designated as lot 1. The decanted liquid was then stirred, and as it came to rest the finest material was again poured off. This was also re-

peated until the water remained clear. The fine sand remaining behind was called lot 2. The turbid liquid was allowed to rest 24 hours, and the sediment which collected constituted lot 3. In introducing his method, Gasparin mentioned the earlier work of Cadet de Vaux, and it therefore is possible that his own method was based on that of de Vaux.

Jackson published a paper on soil analysis in 1846, in which (65) he specified that the soil should be passed through sieves having meshes of 1/10 inch, and 1/50 inch, to remove the coarser particles. The fine material was sedimented by stirring it with water and decanting the turbid liquid. The decantations were repeated until the fine material was removed.

In 1847 Senft (138) discussed the varieties of sand, and followed Schübler in the dimensions given. A section on soil analysis was also included, which was modeled after the Thaer-Davy pattern.

An essay on mechanical analysis was published in 1849 by Schulze (134), who developed the first elutriator ten years before. He mentioned that the resistance offered by water to suspended solids varied according to the surface of the solid, but it increased much more rapidly than the surface. He divided gravel and sand into several grades, but his dimensions did not agree with Schübler's. The classification used by Schulze included large stones, of no definite dimensions, stones, greater than 1 Zoll in diameter, gravel (1-1/8 Zoll), coarse sand (1/8 Zoll-1/3 Linie), "Streusand" (1/3-1/12 Linie), and "Staubsand," so small that the individuals could be seen only with difficulty by the eye.

Schulze criticized the method of analysis used by Schübler on the ground that it was impossible to obtain a check closer than 4 per cent in the fine grades, by repeated analyses. This disadvantage strengthened his determination to continue the use of the apparatus which he had developed. A few modifications were introduced, chief of which was a small spout attached directly to the conical vessel instead of the siphon, and the routine of his analysis was modified to include two round-holed sieves. The soil was sieved to obtain everything larger than "Kies" in the first sieve, and the "grandiger Sand" in the second. The fine material was boiled with water to disaggregate the clay, and poured into the elutriator vessel. Water was run through the vessel with sufficient velocity to carry off the "Staubsand" and everything finer, while the "Streusand" remained behind, and was collected. The finer fraction was allowed to stand for six hours, and the sediment was re-elutriated with a very gentle current, to separate the clay from the "Streusand." The clay was found by difference. Schulze was able to obtain five grades by means of his method. Two of these were obtained by sieving, and three by elutriation. His results were set out in tables of percentages.

The foregoing will demonstrate that Schulze applied himself very intelligently to the problem of mechanical analysis, and he unquestionably did much to pave the way for later more refined methods.

In 1850 Stokes read an important paper (144) before the Cambridge Philosophical Society, in which he discussed the uniform motion of a sphere in a liquid. He arrived at the equation, $-F=6\pi\mu'\rho aV$ to express the resistance of the fluid. In discussing this he said:

> It is particularly to be remarked that according to the formula . . . the resistance varies not as the surface but as the radius of the sphere, and consequently the quotient of the resistance divided by the mass increases in a higher ratio, as the radius diminishes, than if the resistance varied as the surface. Accordingly, fine powders remain nearly suspended in a fluid of widely different specific gravity.
>
> When the motion is so slow that the part of the resistance which depends on the square of the velocity may be neglected, we have, supposing V to be the terminal velocity, $-F=4/3\pi g(\sigma-\varrho)a^3$, where g is the force of gravity, and σ, which is supposed greater than ϱ, the density of the sphere. Substituting . . . we get

$$V=\frac{2g}{9\mu'}\left(\frac{\sigma}{\rho}-1\right)a^2$$

Stokes' formula is now used as the basis of practically all precision methods of mechanical analysis, which depend upon the settling of particles in water, or upon rising currents in elutriator vessels. It was not immediately applied to mechanical analysis by workers in the field, and according to the literature available to the writer, it was not until 1867 that the adoption of Stokes' work by Schöne placed the principles of mechanical analysis on a sound scientific basis.

In 1857 Bennigsen-Förder (11) modified Schulze's apparatus. The original paper was not available, but a description and illustration are to be found in Schumacher (135, pp. 180 ff.), from which Figure 2[4] was adapted. The apparatus consisted of a glass cylinder with four openings along the side, and a long-stemmed funnel which extended almost to the bottom of the cylinder. The three lower openings were closed, and a spout attached to the uppermost. The sample was placed in the cylinder and a current of water, flowing from the bottom of the funnel, carried the finer material in suspension. The very finest particles were carried off through the upper opening, and flowed into a beaker at the side. When the water from this opening remained clear, the second opening was used, and another beaker substituted for the first. This opening carried off the next grade-size, and by continuing the process, the successive levels were tapped in turn. Five grades were obtained by elutriation, including the coarse material in the bottom of the cylinder. Schumacher removed the coarse pebbles with sieves, and rubbed about 5 grams of the sieved soil with a pestle to break up the clumps. The disaggregated sample was transferred to the cylinder, and the process carried on as above.

A total of six grades was recovered, which were the *Schlemmasse* (from the uppermost opening), finest sand, fine sand, coarse sand and small rock-fragments, large rock-fragments and coarse sand, and large rock-fragments (from the sieve).

Schumacher himself substituted a Mariotte bottle for the reservoir tank,

[4] This and subsequent illustrations are to be found in the plates at the end of the paper.

in order to insure a uniform current of water.

At about this time Bennigsen also introduced a "silt-flask" for approximate analyses, according to Wahnschaffe-Schucht (168, p. 24), who cite no references. The flask had a long graduated neck, and after it was filled with the suspension, a cork was inserted and the flask inverted. As the successive layers settled into the neck, the relative amounts of sand and silt could be read directly from the graduations. It will be recalled that Rham had described a similar device in 1840.

Müller modified Schulze's apparatus in 1862 by substituting a retort-neck for the champagne-glass (94), and he separated the sand with sieves having meshes of 2 mm., 1 mm., and .5 mm. Ulbricht (162) introduced a rigorous preliminary treatment of samples for mechanical analysis in 1863. He heated the earth to redness, after which he boiled it in water for one-half hour.

In 1864 a description of Nöbel's elutriator was published in an article by Wolff (184). The apparatus consisted of four communicating pear-shaped vessels. They had volumes in the proportion $1^3:2^3:3^3:4^3$, as shown in Figure 3, adapted from the original. The sample to be analyzed was dried, the larger particles sieved off, and the fine material boiled to break up the clumps. The disaggregated sample was placed in the smallest vessel, and the water turned on for twenty minutes, during which time 9 liters were allowed to flow through the apparatus. This completed the elutriation, and the separates were collected and dried.

In 1865 Müller (95) contributed an interesting method of clearing the clay suspensions which resulted from elutriations. He added ammoniacal soap solution to the turbid water until a foam was generated by shaking. The water was then slightly acidified with acetic acid to precipitate the stearic acid. The precipitate coated the clay particles, and carried them down with it, so that they could easily be filtered off. By subsequent dissolving of the fatty acid (with ether for example), the clay was left behind.

Dietrich described an elutriator in 1866 (36). It consisted of four cylinders of varying diameters and heights, which were inclined to the horizontal. The water entered the bottom of each tube in succession, and flowed from the top. Dietrich removed the larger particles from his samples with sieves, and boiled 30 grams of the fine material with hydrochloric acid before transferring it to his elutriator.

A highly important paper by Schöne appeared in 1867 on the subject of mechanical analysis (128, 129), in which Stokes' law was applied to the problem of separating soils into grade-sizes. He pointed out that spheres settle in water according to Stokes' formula, but that in practice one deals with grains of various sizes, shapes, and specific gravities. Hence it is not possible to obtain a true separation on the basis of any of these factors. Instead, it is advisable to say that the grains that correspond to a given velocity have equivalent "hydraulic values." He also applied Stokes' law to the separation of particles by rising currents of water, and pointed out that

if the water has a given velocity v, a sphere with diameter d, calculated from Stokes' formula, and corresponding to that velocity, is just suspended. If d is smaller than the critical value, the particle is carried away. From actual practice Schöne developed an empirical formula based on Stokes' law, in which v was raised to the 7/11ths power, instead of to the second power, to allow for the variations in shape and specific gravity found among soil particles.

The apparatus devised by Schöne is illustrated in Figure 4, copied from the original plate. The elutriator was based on Schulze's, but modified so that the water entered directly at the bottom of the vessel. A piezometer was attached to the tube to record the pressure of the current. Schöne followed Hundeshagen in treating his samples according to their natures; that is, humus-rich soils were boiled with dilute alkali, etc. After this preliminary treatment he passed the sample through a sieve with meshes of 0.2 mm. The sievings were poured into the elutriator, and the current was regulated at intervals to get the sizes decided upon. In this manner Schöne was able to split the elutriated portion into several fractions in a single operation.

The outstanding features of Schöne's work were his application of Stokes' law to the problems of mechanical analysis, and his clear recognition of the necessity for quantitative work based upon sound scientific principles. Because of these points, the writer is inclined to view his work as the outstanding production of the period, and indeed, to consider him as one who helped place mechanical analysis on a scientific basis. It is noteworthy that the apparatus developed by him is still used, with little modification.

In the year following Schöne's paper, Müller published an important article (97) on mechanical analysis. He divided methods of analysis into elutriation and sedimentation, and pointed out that fine particles could more certainly be studied by sedimentation, and the intermediate ones by elutriation. The coarse material was to be removed by sieving. Müller recognized the necessity of using more than one method on samples having a wide range of sizes, and he devised an elutriator and a sedimentation method which are worthy of note.

Müller's elutriator consisted of a spindle-shaped glass vessel, tapering gradually toward the bottom and more abruptly toward the top, as shown in Figure 5. Water entered the bottom and flowed out of a spout at the top. By varying the size of the upper opening, the strength of the current could be controlled, and a fractional separation effected. In the original apparatus the wire net to be seen just above the lower supporting ring was not present. This feature, called a "Stromausgleicher," was introduced by him (98) in 1877, and was used to equalize the current.

More important than his elutriator, perhaps, was Müller's sedimentation method, in which he anticipated the "pipette method" introduced in recent years by several workers. Müller conducted his analyses by introducing a one-half of one per cent suspension of

fine earth in a glass cylinder. The vessel was shaken and set at rest, and a wooden cover, bearing a series of vertical capillary tubes, was fitted on. The tubes penetrated to different levels below the surface of the suspension, and were bent at right angles at the lower end. They were closed with wax pellets attached to threads which issued from the side of the cover. At the end of a given time-interval the pellet from the uppermost tube was pulled off and 50-60 cc. of the suspension drawn into a pipette. This process was repeated successively with the deeper tubes until a series of samples at varying depths was obtained. The samples were dried and weighed, and by multiplying the weights by a factor based on the volume of the pipette to the total volume, the weights of material suspended at the given depths were found. By computing the settling velocities to these depths, a size-distribution of the material could be determined. Müller's idea for this method resulted from his earlier application of the same apparatus to a study of the rate of rise of cream in milk. The earlier paper (96) was published in 1866.

In 1868 Knop (73) described a method of analysis which yielded two grades by sedimentation and four by sieving. His specifications for the sieve meshes were given in terms of peas, coriander-seeds, and turnip-seeds. In 1871, according to Gessner (48, p. 72), Knop (74) introduced a sedimentation cylinder with four openings arranged in a row on the side, spaced 10 cm. above each other, as illustrated in Figure 6. The openings were closed, a suspension poured into the vessel, and after five-minute intervals the outlets, starting with the uppermost, were opened. This process was repeated until the liquid in the cylinder remained clear, and several grades were thus obtained.

Hilgard (56) described a "churn elutriator" in 1873, in a paper on the analysis of soils and clays. The apparatus is illustrated in Figure 7, and consisted of a glass cylinder, at the base of which was a mechanically operated churn, to break up the floccules that tended to form during the elutriation. He had previously endeavored to eliminate the sediment that accumulated at the base of Schöne's elutriator with a relay reservoir, but he noticed that this sediment contained floccules, and he introduced his churn to eliminate them.

Hilgard boiled his samples in water for about twenty-four hours, and the clay was separated by allowing the suspension to stand for another twenty-four hours, after which it was decanted. The turbid liquid was cleared with brine. After the clay was removed, the sedimented material was sieved to remove the larger grains. The intermediate sizes were fractionated in the churn elutriator. Hilgard recognized 13 size-grades, ranging from grit (3-1/2 mm. diameter), through sand (1/2-12/180 mm.) and silt (9/180-1/1800 mm.) to clay, on which no dimensions were given.

Deetz (35) discussed the requisites of a satisfactory apparatus for sedimentation analysis in 1876. He said the operation must be based upon scientific principles, it must secure an ef-

fective separation of the finest particles, it should avoid large losses of material, it should not use an undue amount of water, and it should preferably be simple and reasonably rapid. On these principles he constructed a cylinder one meter tall and 5 cm. in diameter. At the base of the tube was a bronze casting having in it a series of discs which could be turned to a horizontal position and act as valves. The sample was poured in at the top at a given instant, and as the differential velocities allowed the size-grades to form layers, the lower valves were closed in succession as these layers settled down. After the process was completed, the sediment on each disc was washed into a beaker through an opening in the side of the casting. His apparatus has not been extensively used, and the originator himself pointed out that it did not ideally fulfill the requirements which he postulated.

In 1882 Mayer (89) modified Schöne's elutriator by introducing a separate outflow tube and piezometer instead of the single tube used for both by Schöne. At about the same time Orth introduced a second elutriating tube in series with Schöne's. The bulk of the sample was placed in the auxiliary tube, and only the finest parts were carried over into Schöne's tube proper. Both Wiley (182, vol. 1, p. 242) and Gessner (48, p. 42) mention Orth's tube, but no references were cited.

In 1885 Schloesing (126) introduced his method of analysis, according to Osborne (107). The method involved mechanical subdivision, followed by treatment with acid to dissolve the lime salts, and then by ammonia to dissolve the humus. The clay was separated from the sands by a subsistence period of twenty-four hours, after which it was decanted. This step was repeated several times. The remaining sand was separated into several grades by sieving.

Osborne (107) reviewed the better-known methods of analysis in 1886, and concluded that simple "beaker elutriation" was as effective as any. His method involved successive decantations, such that the liquid decanted contained nothing larger than a desired diameter, and the sediment from this decantation contained nothing smaller. In his analyses, he sieved the sample wet through meshes of 1, 1/2, and 1/4 mm., and separated the fine material into three additional grades by decantation. Material under 0.01 mm. diameter was called clay. In considering the prolonged boiling of samples in water, he concluded that it should be rejected as a preliminary treatment because it abraded the coarser particles and dehydrated and coagulated the true clay.

Claussen (23) modified Bennigsen's silt flask in 1889, according to Gessner (48, p. 73). The sample was boiled in a flask, and when it had cooled, the flask was joined to a long graduated tube, also filled with water, and inverted. The volumes of the sedimented fractions were read directly from the calibrations.

According to Wiley (182, vol. 1, p. 203), Kühn introduced his silt cylinder in 1889. It consisted of a glass cylinder (fig. 8) about 30 cm. tall and

5 cm. in diameter. Five centimeters from the bottom was an outlet, which was kept closed during the sedimentation and opened at the end of a chosen interval to drain off the turbid liquid. By repeating the process at different intervals, several grades could be obtained. In 1891 a modification of this cylinder by Wagner was mentioned in a report (185) by a committee on soil analysis. Wagner substituted a siphon for the side outlet. The siphon was lowered to the bottom of the cylinder, and the liquid drained through it. In the same report was included a grade scale proposed by Wagner.

Briggs, Martin, and Pearce (18, p. 7) mentioned that the earliest use of centrifugal force in mechanical analysis was made in 1892 by Whitney, who used a Babcock hand separator to hasten sedimentation by the beaker method.

A review of current methods of mechanical analysis was published in 1893 by Hilgard (57). He paid particular attention to the churn elutriator, which was used in his own laboratory. An excellent photograph of the set-up may be seen on page 253 of his report.

According to Slichter (140), Hazen (55) used cumulative curves to represent the mechanical composition of sands and gravels in 1892. This is the earliest use of typical statistical curves applied to sediments that has come to the writer's attention.

In 1894 Appiani (4) described a sedimentation cylinder. A tube with an inverted mouth extended several centimeters above the bottom on the inside, and was controlled by a stopcock below the tube. The suspension was poured into the cylinder and after a given interval the liquid was drained out to the level of the outlet, without disturbing the sediment which had accumulated below. This process was repeated until the desired separation was completed.

Williams (183) published an essay on mechanical analysis in 1895, in which he compared the better-known methods of analysis. He advanced Fadejeff's method as an improvement over the others, but gave no references to Fadejeff's publications. The method involved a series of cylinders into which the suspensions were successively decanted to separate the several grades. The process was extremely tedious, and involved boiling the sample for forty-two hours during the analysis. The finest particles were coagulated with calcium chloride after the coarser material had been separated. In the same paper Williams gave a classification of soil particles ranging from stones (greater than 10 mm. diameter) through gravel (10-3 mm.), sand (3-0.25 mm.), "dust" (0.25-0.0015 mm.), to "clay" (under 0.0015 mm.).

In 1895 Snyder, according to Briggs, Martin, and Pearce (18), used a centrifuge in his analysis, and Hopkins (62) in 1899. Both of these were essentially applications of centrifugal force to the beaker method, and were used to separate the silt from the clay.

Udden's paper on wind deposits (160) appeared in 1898, and in it he established the geometric grade-scale which is essentially the same as that now in general use in America. His

grades ranged from coarse gravel (8-4 mm. diameter) to very fine dust (1/128-1/256 mm.) in such manner that "the diameters of the largest particles in one grade have twice the diameter of the coarsest particles in the next finer grade." Udden ran his analyses with sieves down to 1/8 mm., and below this by microscopic measurement. His data were set up in frequency diagrams, and as far as the writer is aware, this is the earliest use of these diagrams to represent the size distribution of sediments.

In 1899 Hopkins (61) pleaded for a scientific basis for the division of soil particles into grades, and suggested a scale of sizes based on the square root of 10. The scale started at 1 mm., and extended successively to 0.32 mm., 0.1 mm., 0.032 mm., etc.

THE TWENTIETH CENTURY

The tremendous increase in the papers which appeared on mechanical analysis since 1900 renders it impossible to discuss the contributions in chronologic order without introducing a complexity of isolated paragraphs. The writer has therefore decided to alter the mode of presentation in the remaining part of the paper, and to treat subsequent developments according to subject, arranged chronologically within each unit. The papers will also be discussed more briefly, because the availability of recent publications renders it unnecessary to describe them in as great detail. Readers interested in particular techniques will find ample material in the appended bibliography.

METHODS AND APPARATUS

DECANTATION METHOD

Among the methods which had been established prior to 1900 was the simple decantation method, and its use has continued into the present century. In 1904 Hall (53) described a method based on the earlier work of Schloesing, in which the clay was decanted after a subsidence period of twenty-four hours. In the same year Briggs, Martin, and Pearce (18) used a centrifuge to separate the clay from the silt, after the fine material had been decanted from the sand. The centrifugal method was slightly modified in 1912 by Fletcher and Bryan (42). According to Goldman (50), Thoulet (154) described a method in 1907, in which the sample was shaken in ammoniacal water for thirty hours and poured into a dish, from which the fine material was decanted. In 1915 Robinson (117) studied the effect of changes in temperature on decantation analyses, and suggested 12-14°C. as the most favorable. Trask (156) described a decantation cylinder in 1930, in which a detachable cup on the bottom facilitated removal of the sedimented material.

SEDIMENTATION CYLINDERS

Cylinders of the type devised by Knop and Kühn have received some attention since 1900. The most important development was made by Atterberg (6) in 1912, who attached a glass tube on the side of the cylinder a short distance above the bottom, to drain off the turbid liquid, as shown in Figure 9. The outlet was controlled by a pinchcock on a rubber tube. At-

terberg's cylinder achieved considerable popularity in Europe, and several writers have either criticized, defended, or slightly modified it. Among these commentators were Richter (114), Van Zyl (166), Von 'Sigmond (167), and Köhn (77). In 1912 Stone and Chapman (145) introduced a sedimentation cylinder in which the suspension was centrifuged and the sediment volumetrically determined. Doerell (37) referred in 1922 to a cylinder developed by Sikorsky, in which a combination of Kühn's cylinder and Bennigsen's silt flask were used. In 1926 Wentworth (172) revived Wagner's use of a cylinder and siphon. In 1929 Kühl and Czernin (82) described a variation of Knop's cylinder with nine spouts. The sample was introduced in the top of the cylinder and the spouts were used to drain off the fractions as they distributed themselves according to their velocities. According to Odén (104), Schloesing (127) devised a sedimentation cylinder in 1903 which included an automatic device for collecting the separates in small moving compartments below the cylinder. The cylinder was so arranged that the sedimented material issued at intervals from a small orifice at its base. The original illustration of this somewhat complicated apparatus is reproduced in Odén's paper, which credited Schloesing's work as the earliest attempt to estimate the weight of an unlimited number of fractions of decreasing settling velocity.

RISING CURRENT ELUTRIATORS

Several workers devoted their attention to rising current elutriators since the beginning of the century. Kopecký (79) described his apparatus in 1901. It consisted of three vertical cylinders with conical bottoms, arranged in series. The water flowed in at the bottom and out of the top of each in turn. The respective diameters of the cylinders were 3.0, 5.6, and 17.8 cm. Figure 10 illustrates the device, which may be taken as typical of the multiple-tubed elutriators. In 1904, according to Briggs, Martin, and Pearce (18), Yoder developed a centrifugal elutriator in which a specially constructed tube enabled him to centrifuge a soil suspension continuously. The suspension was fed into a funnel, and as it passed through the centrifuge tube, a separation into sizes was effected which depended upon the velocity of the stream and the speed of the centrifuge. The water containing the finest material issued from the centrifuge into a spray collector. In 1904 Krehbiel (81) used a battery of three cylindrical vessels with conical bottoms and outlet tubes on their sides. The current was directed to the bottom of the vessels through a tube, after the manner of Schulze. In 1911 Bollenbach (14) modified Schöne's elutriator by introducing an inlet tube very much like that in Schulze's original apparatus. Crook (54) introduced his elutriator in 1913; it had a large cylinder with a conical bottom attached to a narrow cylinder below. With this arrangement Crook obtained sand in the lower cylinder, silt in the upper, and the clay-water flowed into beakers on the side. In 1920 Gardner (45) developed an elutriator having 19 cylinders ranging in diameter in

arithmetic progression from 4 to 40 cm. A current of the suspension entered the bottom of the smallest cylinder, and left it through a conical cap, entering the second through a conical base, and so on. Due to the arithmetic increase in the diameters of the cylinders, the diameters of the grades obtained diminished in harmonic progression. In the same year Schurecht (136) modified Krehbiel's elutriation battery by using four gold-plated cans, and improving the overflow arrangement. In 1922 Lowry (87) used a single-tube elutriator with a graduated tube at the bottom for the volumetric measurement of the particles which remained behind after the separation was completed. Andreason (2) described an elutriator in 1923 which had three cylindro-conical vessels arranged in series much like Kopecký's. It differed from Kopecký's in several respects, among which was the introduction of water into the first two vessels through a narrow tube which extended to their bottoms, after the fashion of Schulze's earlier method. General discussions and critiques of elutriator methods were published by Boswell (15), Koettgen (76) Köhn (77), Lowry and McHatton (86) and Richter (115). Gessner (48) included considerable material on the subject.

AIR ANALYZERS

The use of air currents to separate fine particles has received considerable attention, especially in its application to the study of pigments, cement, and ceramic materials. In 1906, according to Roller (120, p. 6), Gary (46) described an air separator which consisted "essentially of a conical container for the powder charge surmounted by a tall cylinder. The air blast impinging vertically on the powder blows out the fine particles." Another early air elutriator was introduced in 1907 by Cushman and Hubbard (28). Five percolating jars were arranged in series, as shown in Figure 11. The first two had capacities of 3 and 2 gallons respectively, and the last three of 1 gallon. An air blast was attached to the bottom of the first jar, and a series of tubes conducted the current through the others in turn. The sample of dry powder was placed in jar no. 1, and successive sizes of particles were carried by the blast into the other four. A suction device was attached to the last jar, and the current so adjusted that none of the powder was carried out of the system. In 1915 Pearson and Sligh (110) introduced an air analyzer constructed similarly to Gary's, but the stack was automatically tapped during the analysis. These writers also included an excellent review of earlier work in their paper. In 1930 Roller (120) constructed a cylindrical separator with a conical top and bottom. The sample was placed in a U-tube at the bottom of the main chamber. A blast of air entered one end of the tube, which was agitated by an automatic hammer so that fresh portions of the powder were continually exposed to the blast. The suspended fractions collected in a paper thimble at the top of the main chamber; by varying the strength of the current, the sizes of the fractions could be controlled to within very narrow limits. He was able to effect sepa-

rations down to less than 3 microns in some cases. Roller also furnished a thorough review of methods of analysis and he discussed other workers in the field not mentioned in this paper.

CONTINUOUS SEDIMENTATION BALANCE AND THEORY OF SEDIMENTING SYSTEMS

In 1915 Odén (103) described his continuous sedimentation balance, which afforded a new method of obtaining the distribution curves of sediments without isolating the various grades. His apparatus consisted of a balance pan, suspended near the bottom of a cylinder of soil suspension, upon which the falling particles accumulated. This pan was counterpoised with another in such a manner that when the sediment lowered the pan below a certain level, shot were automatically released into the counterpoise by an electrical control. By observing the increase in weight P of the accumulated sediment with time t, a settling curve $P(t)$ was obtained, from which the distribution curve was computed. The essential parts of the instrument are shown diagrammatically in Figure 12.

Fully as important as the sedimentation balance was Odén's development of a mathematical theory of sedimenting systems. As presented in his original paper (103), this theory involved the application of Stokes' law, but Knott (75) showed that the equations could be solved without it, and the full theory was developed by Fisher and Odén (41) in 1923. Odén (104) reviewed it in 1925, and this latter paper is considered here. A soil suspension is assumed to have complete dispersion and uniform distribution of the particles, to be at a constant temperature, and to have a concentration so dilute that the particles do not interfere with each other during their descent. If G is the total weight of particles suspended in a volume V of water, and s the specific gravity of the particles, then at time t_0 every cubic centimeter of the suspension contains G/V grams, or G/Vs cc. of solid particles, and therefore $(1 - G/Vs)$ cc. of water. Hence the specific gravity g of the suspension at a depth x at the start is:

$$g_0 = 1 - \frac{G}{Vs} + \frac{G}{V} = 1 + \frac{G}{V}\left(1 - \frac{1}{s}\right).$$

At time t and depth x, there will remain zG gm. of particles per V cc., because all particles with velocity v greater than x/t will have settled below the layer, and those whose v is less than x/t will remain in the same concentration as at the start. Hence,

$$g = 1 + \frac{zG}{Vs}(s - 1),$$

or $g = 1 + cz$, where

$$c = \frac{G(s - 1)}{Vs},$$

a constant under the given experimental conditions. If a be the area of the base of the column of suspension, then $V = ax$, and

$$cx = \frac{1}{a}\frac{G(s - 1)}{s} = \frac{G}{a}\left(1 - \frac{1}{s}\right).$$

The right hand side of the equation represents the weight in the liquid of the particles which will ultimately settle on a unit area of the base of the

column, and if A is the total weight (in the liquid) of particles deposited in a very long time, then $cx=A/a$.

From the preceding equations the theory of the various methods which may be employed to obtain the distribution curve was developed, with the use of certain auxiliary equations based on $v=x/t$, such as the derivative and the partial derivatives. Four methods are shown to be available. They are (1) measurements of the variations of density, (2) measurements of the variation of hydrostatic pressure, (3) measurements of change of weight of an immersed body, and (4) measurement of weight of sediment deposited from a suspension.

It will be seen that Odén's balance belongs to Type 4 above, which according to him furnishes the most accurate method of determining the ordinates of the distribution curve. After the curve is obtained, data for both the cumulative curve and for frequency diagrams are determined graphically by setting tangents to the distribution curve at given ordinates, and reading the values intercepted on the Y-axis by these tangents.

Odén's work stands out as of paramount importance to mechanical analysis, and his researches have opened a number of avenues for additional investigations. Numerous workers have since used or modified his original balance, and new apparatus was developed to exhaust the other possibilities of the mathematical theory. The former only will be considered at this point. In 1923 Johnson (68) added an automatic device which punctured holes in a record on a revolving drum by sending electric sparks through at intervals. In 1924 the Odén-Keen modification (70, pp. 82 ff.) was advanced, which gave a continuous graphical record of the curve through electromagnetic control and a weight-dropping device. In 1925 Coutts and Crowther (26) discussed a source of error in the method, caused by certain currents set up during the subsidence. Werner (175) adapted a volumetric device for obtaining the settling curve, and Schramm and Scripture (130) utilized a series of test tubes to obtain the curve, instead of the balance. In their method, given volumes of suspension were poured into a series of tubes, and the liquid above a mark on the side was drained from successive tubes at stated intervals. The sedimented material was dried and weighed, to determine how much had accumulated during the intervals. The data so obtained served as points on the settling curve. In 1930 Trask (157) applied centrifugal force to aliquot portions of the sample to hasten sedimentation of the smaller particles. The centrifuged sediments were weighed and the curve constructed from the data obtained.

CONTINUOUS SEDIMENTATION CYLINDERS

In 1918 Wiegner (179) introduced a manometric sedimentation cylinder which rested upon the principle that two columns of liquid of different specific gravities will rise to levels inversely proportional to their densities, when confined in separate tubes which are joined at some point. The apparatus consisted of a long cylinder to which was joined a parallel mano-

metric tube of about the same length, as shown in Figure 13. A stopcock controlled the point of juncture, and with this closed, water was poured into the manometer and the soil suspension into the cylinder. When the stopcock was opened, the manometer registered the hydrostatic pressure at the point of juncture, and as particles settled below this level, the pressure dropped. By observing the decrease in pressure as a function of the time, a curve was constructed from which the distribution curve could be computed. The principle used by Wiegner is thus related to the second type of possible methods mentioned by Odén.

Wiegner's apparatus was improved in 1922 by Gessner (48, p. 98), who added a photographic device which obtained a continuous record of the curve. Zunker (186) in 1923, added an auxiliary tube near the top of the main cylinder so that the differences in height of the two columns could more accurately be determined. Kelley (69) in 1924, bent the manometric tube at an angle to magnify the differences in pressure and to make possible a more precise reading. In 1932 Sumner (147) used the device with the manometric arm bent horizontally and with benzene as the index liquid. A discontinuous recording camera obtained the record of the analysis. In 1932 Barnes (8) used a needle geared to a dial on the manometer to obtain precise readings of the water level. A galvanometer announced contact of the needle with the water. Modifications of a different sort were made by Ostwald and Von Hahn in 1922 (108). The first modification was to place the stopcock at the upper end of the manometer tube, and the second involved the use of a single tube in which the suspension as a whole rose in the tube under the influence of atmospheric pressure, as particles sedimented from the tube into a vessel below. Odén (104) modified Wiegner's tube by using pentane as the manometer fluid in 1925. He also improved the contact between the two liquids by suspending the manometer tube in the main cylinder. In 1927 Tuorila (158) used two separate manometric tubes on Wiegner's apparatus to correct the readings for the effects of flocculation.

In 1927 Crowther (27) introduced a manometric sedimentation cylinder similar in general principle to that of Wiegner, but differing in that the hydrostatic pressure was measured at two points in the suspension. The essential details are shown in Figure 14, which illustrates the manometer. Aniline was used as the index liquid and it measured the density of the suspension at the point midway between the two tubes. By an adjustment of the graph obtained, Crowther converted his results directly into a summation curve. In the same year Lukirsky and Kosman (88) published a description of a device built along the same lines, except that three tubes of equal diameter were used. One of them contained the suspension, and the other two were filled with water and served as measuring tubes of the hydrostatic pressure between chosen points in the suspension. This measurement was accomplished by having several small tubes joining the sedimentation cylin-

der to equivalent points on the two measuring tubes. Each juncture was controlled by a stopcock, and during the analysis two sets of stopcocks were opened, to measure the variations in the hydrostatic pressure between the chosen points.

THE PIPETTE METHOD

In 1922-23 three independent papers by Robinson (118), Jennings, Thomas, and Gardner (67), and Krauss (80) appeared on the pipette method of analysis. This method rests on the principle that in a dilute suspension the particles fall as individuals, and by permitting all grains having a given velocity to settle below a certain level, a sample taken at that level at the critical time will contain the full concentration of all material having a lesser velocity. By taking samples from the given level at various intervals, the concentrations of successively smaller particles may be found, and by subtraction the amount of material in any grade may be computed. The samples are usually 10 or 20 cc., and the suspension is well shaken between samplings. This method is obviously related to Odén's theory, and belongs to Type 1.

Robinson used an ordinary pipette to sample his suspensions, and thus introduced the simplest of the three devices for pipette analysis. Jennings, Thomas, and Gardner used a "multiple-intake pipette" with the openings turned in a horizontal position to drain off the samples. The pipette was permanently fixed in the bottom of a cylinder, and the sample could be withdrawn by opening a pinchcock below. Krauss used a series of three pipettes with side openings, which could be introduced to the desired depth in the suspension by a rack and pinion. The system was so arranged that exactly 10 cc. were withdrawn and drained into a beaker. His apparatus is shown in Figure 15 as representative of the types of apparatus used. In all three methods the coarse material was first screened off and the fine material dispersed by physical or chemical means.

In 1926 a subcommittee of the A.E.A. of Great Britain (1) compared several methods of analysis and recommended the pipette method as the standard for routine soil analyses. It was also adopted as the international method, and it has replaced the earlier centrifugal method of the U. S. Bureau of Chemistry and Soils.

In 1928 Köhn (77) developed an apparatus similar in some respects to that of Krauss, but using only one pipette. In the same year Andreason (2) used a constant temperature chamber for the suspension. In 1930 Olmstead, Alexander, and Middleton (106) described the apparatus used by the Bureau of Chemistry and Soils. The pipette was a Lowy automatic, equipped with a stopcock having an air vent. The pipette was clamped to a support and lowered by rack and pinion to the desired depth.

THE HYDROMETER METHOD

Bouyoucos (17) introduced the hydrometer method of mechanical analysis in 1927. The soil was dispersed, and after dilution with water, the density of the suspension was read at intervals with a hydrometer. From the

data obtained a distribution curve was constructed. A special hydrometer and dispersing machine have since been introduced (16), to effect greater standardization of the technique. Richter (115) suggested a temperature correction for the method in 1931. In 1932 Puri (112) introduced a new type of hydrometer, which consisted of a short bulb on a long stem. The readings were made in reference to a pin on the top of the stem, the level of which was read from a burrette tube clamped above the apparatus.

Closely related to the hydrometer method is the use of a plummet submerged in the suspension and attached to a balance. By observing the change in the apparent weight of the plummet with time, the changes in the density of the suspension may be computed and a curve drawn. Schurecht (137) used such a method in 1921, and Van Nieuwenberg and Schoutens (164) in 1928.

TURBIDITY OF SUSPENSION METHOD

By photographic measurement of the turbidity of a suspension in relation to time, it is possible to compute the concentration of particles in the suspension and their size distribution. In 1921 Scales and Marsh (125) used a tyndallmeter to measure the amount of material in soil suspensions, but no attempt was made to work out the size distribution. Svedberg and his coworkers, however, have used turbidity to determine size distribution, and the results were verified by microscopic counts. A special centrifuge was developed by Svedberg and Nichols (149) in 1923 which permitted the suspension to be photographed while being precipitated. A uniform beam of light was sent through the tube and the variation in the concentration of the particles was studied. The size distribution was determined from the data so obtained. In later papers Svedberg and Rinde (148, 150) and Stamm and Svedberg (142) further developed their researches. In 1925 Morison (92) applied the general method to soils by photographing the suspensions through a Goldberg wedge. From the points of equal density, data were obtained for constructing a curve. Morison concluded, however, that a complete interpretation of the results involved a knowledge of laws not yet possessed.

DISPERSION

The preliminary dispersion of samples for mechanical analysis has received increasing attention in recent years, especially since the introduction of precision methods of analysis. It has been a common practice for workers on methods to introduce their own procedure for dispersion, so that considerable variation is to be found in the literature.

Among the physical methods of dispersion, one of the oldest is boiling, and it has been both praised and condemned in recent years. Von Hahn (52, p. 23), referred to the "barbaric" method of boiling samples, but Gessner (48, p. 163) inclined to the notion that in electrolyte-free suspensions it was justified. Simple rubbing in water with a stiff brush or a rubber pestle was another early procedure, used by Beam (10) in 1911, and since then

by many workers, usually in combination with other devices. Shaking the sample in water with small amounts of sodium carbonate or ammonia was used in 1904 by Briggs, Martin, and Pearce (18). It has grown to be one of the standard methods, and in 1925 Puri and Keen (111) determined the rate of dispersion effected by shaking samples under standard conditions for greater or lesser periods of time. In the same year Davis (30) used small rubber balls in the bottles to hasten dispersion. In 1924 Whittles (177) used a vibrating machine to disperse his samples, and in 1931 Olmstead (105) used supersonic waves for the purpose. The supersonic vibrations were produced by a piezoelectric quartz crystal immersed in an oil bath. The energy was transmitted through the oil into an Erlenmeyer flask containing a water suspension of the soil. Bouyoucos (16) used an electric drink-mixer to stir his samples in 1927, and in 1928 Baver (9) slightly modified the procedure. Nostitz (101) endeavored to obtain the effect of "cold boiling" by drawing air through his samples, and in 1928 Van Nieuwenberg and Schoutens (164) used compressed air to get their samples in suspension.

Among the chemical agents used to aid dispersion, sodium carbonate or ammonia were most widely used, but other chemicals were used in special cases and by some workers. Groves (51) used ammoniacal hydrogen peroxide on ferruginous soils in 1928, Bouyoucos (16) recommended dilute potassium hydroxide, and Olmstead, Alexander, and Middleton (106) decided upon sodium oxalate in 1930. In the event that electrolytes which tend to flocculate the suspension are already present, preliminary dialysis has been recommended. Gessner (48, p. 164) discussed this procedure at some length.

Several workers have published comparisons of various methods of dispersion in which the effects of boiling, shaking, vibration, dialysis, etc., were considered. Such comparisons were made by Richter (114) in 1916, Nolte (100) in 1919, Hissink (59) in 1921, Whittles (177) in 1924, Wiegner (180) in 1927, Davis and Middleton (31) in 1928, and Dragan (38) in 1931.

GRAPHIC PRESENTATION OF DATA

The use of graphs for presenting the results of mechanical analyses has increased greatly in recent years, and applications of statistical methods to such data have been made by several workers. Frequency pyramids and cumulative curves had been used since the close of the nineteenth century, and in 1920 Baker (7) used cumulative curves to derive his "equivalent grade" and "grading factor" as measures of the size and sorting of sediments. In 1921 Dake (29) described the characteristics of cumulative curves as applied to sands, and in 1924 Robinson (119) found them to be sigmoids and recommended their use because smoothing presented no great difficulties. In 1923 Holmes (60) devoted considerable space to methods of presenting data by means of curves, triangle diagrams, and the like. Van Orstrand (165) in 1924 discussed the

possibility of representing distribution with Pearson's frequency functions. He applied these statistical methods to sands and computed the mean, the mode, the standard deviation, and skewness. In 1926 Wentworth (172) included a section on graphic presentation in his *Methods of mechanical analysis of sediments*, and considered frequency pyramids, cumulative curves, and the transformation of one grade-scale to another. Steiger included a section on graphic presentation in the *Treatise on sedimentation* (159). Calbeck and Harner (21) discussed sedimentation curves and frequency pyramids in 1927. In 1929 Wentworth (174) published a detailed account of a method of determining the statistical constants of sediments by computing the mean, the standard deviation, and skewness. In 1930 Trask (157) briefly considered the use of the median and the quartiles for characterizing sediments, and in 1931 Tickell devoted a section of his *Examination of fragmental rocks* (155) to the statistical treatment of data, by computing skewness and kurtosis from the percentiles.

The introduction of the continuous sedimentation balance by Odén in 1915 involved also the introduction of new methods of graphic presentation, inasmuch as his sedimentation curves measured the increase in the weight of sediment deposited, as a function of the time. The curves were thus not direct expressions of the relative amounts of any particular grade-sizes, but rather a composite picture of the sediment. These curves in themselves have proved valuable in representing the characters of sediments, but Odén showed that they may be converted into cumulative curves or into frequency pyramids by computation or graphically. It has been mentioned above that this may be done by drawing the tangent to the curve at a given ordinate and determining the intercept of this tangent on the Y-axis, which furnishes a direct reading of the amount of material greater than the given radius. This is equivalent mathematically to obtaining the derivative (which measures the slope of the tangent) at the given point, and multiplying it by the time. The desired amount w is then the total weight W accumulated in time t, minus the derivative of the total weight with respect to time, multiplied by the time: $w = W - t.dW/dt$. In Wiegner's method a curve is obtained which reflects the decrease in pressure in the manometric tube as a function of the time, and this curve is amenable to the same treatment as Odén's curves for the determination of the cumulative curve and the frequency pyramids.

GRADE-SCALES

Among grade-scales advanced for sediments,[5] one of the most widely used in America was that of Udden, proposed in 1898, and expanded by him (161) in 1914 to extend from

[5] A considerable number of grade-scales have been proposed by various workers, especially for the screening of industrial powders, and these have included systems based on the square root of 2, the 4th root of 2, the cube root of 3, etc., in terms either of inches or millimeters. These proposals, and others, were reviewed in an interesting booklet, *The profitable use of testing sieves*, Cleveland, 1930, issued by the W. S. Tyler Company.

large boulders (256-128 mm.) to fine clay (1/1024-1/2048 mm.). Throughout these ranges each succeeding grade-limit was half that of the preceding. In 1922 Wentworth (171) observed that such terms as "boulder," "cobble," etc., were still loosely used, and he endeavored to standardize the terminology by suggesting a grade-scale based on a comparison of the usages of numerous workers. His suggestions were adopted practically without exception by American workers.

The grade-scale most commonly used in England is that of Boswell, according to Milner (90, p. 108). This scale ranges from gravel to clay, and the succeeding grade limits are 2 mm., 1, 0.5, 0.25, 0.01, 0.05, and 0.001. mm. On the Continent the grade-scale proposed by Atterberg (5) in 1905 met with considerable approval. His classification, according to Rubey (122), extended from boulders (greater than 2000 mm.) to clay (less than 0.002 mm.). The grade limits were each 1/10 of the preceding: 2000 mm., 200, 20, 2, 0.2, etc., and each group was subdivided into three fractions. The scale was based on diameters at which pronounced changes in the physical properties of the particles became noticeable.

The grades used by soil scientists in America have differed in several respects from those of workers on sediments. The greatest difference lies in the absence of a uniform ratio between the successive grades, except in that proposed by Hopkins, whose system was not widely used. In 1904 Briggs, Martin, and Pearce (18) compared the scales used by Hilgard, Osborne, and Hopkins, and adopted a scale similar to Osborne's. The limits decided upon were: 2 mm., 1, 0.5, 0.25, 0.01, 0.05, and 0.005. In the higher divisions the ratio is geometric, but in succeeding sizes the proportions change.

GENERAL REFERENCES AND TEXTS

General discussions of methods of mechanical analysis were published by numerous writers, either in papers or in volumes on sedimentary petrology. In 1909 Parmelee and Moore (109) compared several of the older routine methods, and decided that the centrifugal method was best. Novák (102) compared the methods of Atterberg, Kopecký, and Kühn in 1916. In 1921 Wightman and Sheppard (181) published a review of the methods available for size distribution analysis. Kuhn (83) published a general discussion of the more recent precision methods in 1925. In 1927 Wentworth (173) considered the accuracy of mechanical analysis, based on experiments conducted with the sieving of sands. In 1928 appeared papers by Köhn (77) and Andreason (2) on the general principles of mechanical analysis.

Text and reference books either devoted to mechanical analysis, or in which methods are included, were written by Hilgard (58) and Wiley (182) in 1906, Hatch and Rastall (54) in 1913, Mitscherlich (91) in 1920, Keilhack (71) in 1922, Holmes (60) in 1923, Wahnschaffe-Schucht (168) in 1924, Wentworth (172) and Twenhofel (159) in 1926, Ries (116) and Russell (124) in 1927, von Hahn (52)

in 1928, Milner (90) in 1929, Emerson (40) in 1930, and Gessner (48), Keen (70), and Tickell (155) in 1931.

CONCLUDING REMARKS

Since an organized interest in the composition of soils far antedated an equally developed interest in sediments, sedimentary petrologists have largely adopted methods of mechanical analysis already developed by soil scientists. However, the methods chosen were often not the more precise or scientific, and the writer would like to emphasize the necessity of considering more critically the particular techniques which have been proposed as suitable for sediments. He would like to recommend the pipette method to the consideration of workers in fine sediments as one founded upon sound principles, and yet simple and inexpensive in its application. He has used it with success on fine-grained sediments ranging from lake clays to the finer constituents of tills, with checks on successive analyses consistently within 1 per cent. Further, it enables analyses to be made down to 1/1000 mm. at the rate of three or four a day. Interested readers are referred particularly to the paper by Olmstead, Alexander, and Middleton (106) for details. In a forthcoming paper the writer proposes to describe an adaptation of the method to sediments.

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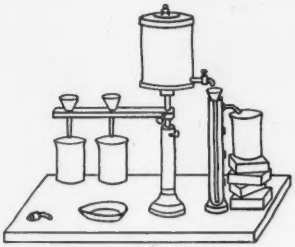

Fig. 2
Bennigsen-Förder, 1857

Fig. 3
Nöbel, 1864

Fig. 4
Schöne, 1867

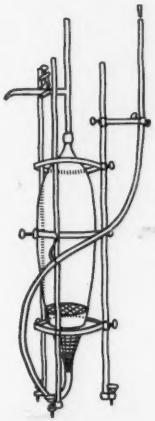

Fig. 5
Müller, 1868

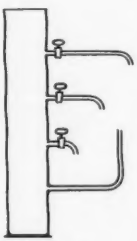

Fig. 6
Knop, 1871

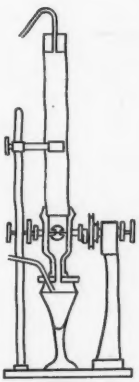

Fig. 7
Hilgard, 1873

Fig. 8
Kühn, 1889

Fig. 9
Atterberg, 1912

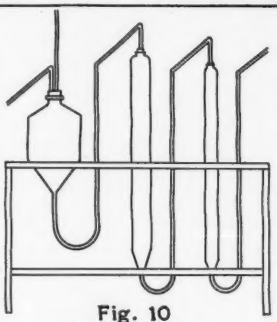

Fig. 10
Kopecký, 1901

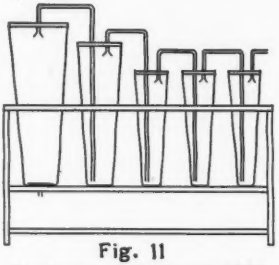

Fig. 11
Cushman-Hubbard, 1907

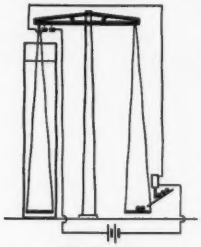

Fig. 12
Odén, 1915

Fig. 13
Wiegner, 1918

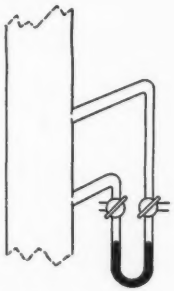

Fig. 14
Crowther, 1927

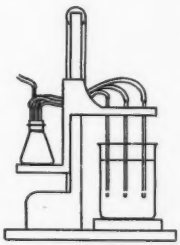

Fig. 15
Krauss, 1923

NOTES

CELLOPHANE AS A SLIDE COVER

The many common commercial uses of cellophane have demonstrated its strength and durability and its adaptability to uses in the laboratory. No doubt the same idea has occurred to other workers but a suggestion may come to some from this statement.

Cardboard slides with a cut-out are used commonly to mount foraminifera and other small organisms or mineral grains. The writer uses such slides with a thin cover glass inserted at the bottom of the cut-out when a stronger light effect is wanted on the under side of the mounted mineral grain. The grains may be cemented to the glass with glue or Dupont household cement, or left unattached. The opening in the slide is covered with a strip of cellophane which is cemented to the top of the slide.

A very satisfactory method is to cut the cellophane strip about one-fourth inch wider than the diameter of the opening and long enough to turn the ends of the strip to the under side of the slide. A very small amount of cement applied with a small brush will suffice. The strip is placed over the opening with the ends extending beyond the edge of the slide and held in place by a second or dummy slide. One end of the cellophane is cemented to the under part of the slide being mounted, and held in place with the finger that is clamping the two slides together. The other end of the cellophane is pulled tight and also cemented to the under side of the slide. If care is used to pull this strip taut a smooth and dust-proof cover will result.

The advantages of cellophane over a thin cover glass are apparent. The slide with cellophane can be dropped on the floor, it can be pressed in handling and subjected to general rough usage without destroying the even and tight seal. Cellophane is about one-fifth the thickness of the medium-grade cover glass and when high power objectives are used this is a distinct benefit. The ordinary cover glass is easily broken if the objective touches it, but cellophane is strong enough to yield slightly without breaking and the danger of scratching the front lens of the objective is lessened. Use in the laboratory by inexperienced students of the cellophane cover has saved a large number of slides.

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A COMMITTEE FOR THE STUDY OF ACCESSORY MINERALS OF IGNEOUS AND SEDIMENTARY ROCKS

The Division of Geology and Geography of the National Research Council has announced a new Committee to study the Accessory Minerals of Crystalline Rocks. Special attention will be given to the nature of such minerals, their variation in time and space in igneous bodies and metamorphosed masses of characteristic accessory minerals. This is not a new idea, but there is a great need for accurate data which will serve to differentiate igneous masses over a wide area; with a few exceptions little is known regarding the differences in different parts of a single intrusion or in successive intrusions from a single magmatic source. Work of this type is already under way at several institutions and the committee will serve to correlate the results and encourage further studies.

The students of sedimentary rocks in the academic and commercial fields should welcome the work of this committee. As the ultimate source of the sedimentary rocks is in the igneous masses, little ex-

planation need be given to show the importance of this work to the petrologist of sedimentary rocks. How convenient and enlightening it would be to be able to check and compare the accessory minerals (the so-called "heavies") of the formations flanking the granite ridge of Kansas with the accessory minerals in the fresh granite cuttings. Or even better, new data concerning a division of the Permian-Pennsylvanian of central Colorado may be had from a critical study of the accessory minerals in the thick clastic series of that locality. It is possible that with a differentiation of the old igneous masses now exposed in the mountain cores, the distribution of exposures during the Pennsylvanian and Permian periods can be checked and evidence pointing to physical changes of land and sea can be obtained. These are merely illustrations of the way such studies can be used.

Some investigators have questioned recently the value of heavy mineral studies in connection with the correlation of sedimentary rocks. Numerous well-known failures back these arguments, but in reply it may be said that the workers have had too little information and with more complete data and a greater refinement of technique some success may be expected.

European students of sediments have appreciated the value of such studies for many years. In the British literature one finds numerous accounts of studies of the source of accessory minerals of the sedimentary rocks. This work has demonstrated the need for more accurate information on the minerals of the igneous masses and shows the successful use of the information when properly handled.

The committee is headed by Prof. A. N. Winchell (Wisconsin) and consists of Prof. E. S. Larsen (Harvard), Dr. J. C. Reed (U. S. Geological Survey), Prof. J. E. Stark (Northwestern), Dr. J. F. Wright (Can. Geol. Surv.) and Prof. A. C. Tester (Iowa). An examination of the literature dealing with the petrography of sediments is now being made by the last named member of the committee. Considerable work has been done and the results will appear later in the annual report of the committee. Suggestions from other students of sediments will be welcome, as well as assistance in finding pertinent, but obscure, publications.

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REVIEWS AND NEW PUBLICATIONS

GESSNER, HERMANN, *Die Schlämmanalyse,* Volume 10 of *Kolloidforschung in Einzeldarstellungen.* Leipzig: Akademische Verlagsgesellschaft, 1931. Pp. x+244; figs. 102; pls. 1. 18 M. $4.50.

In this compact volume Gessner has included a wealth of material on the theory and practice of mechanical analysis. Although it was not written primarily from the point of view of sedimentary petrology, workers in the field will find an ample choice of methods for their particular problems among the wide variety offered.

The book is divided into three chapters and an appendix. The first chapter discusses the underlying principles of the settling of small particles in fluids, and the effects and causes of flocculation. Starting from Stokes' formula, the author develops the assumptions upon which it is based, and the limitations met when it is applied to mechanical analysis. Various attempts to modify the formula, and corrective factors which have been proposed by others, are presented in detail. Flocculation is treated largely in an endeavor to develop a mathematical expression for the phenomenon: an admittedly difficult matter in polydisperse systems.

The second chapter is devoted to a description of methods of analysis, and includes numerous older techniques as well as others more modern and precise. They are divided into sedimentation-methods, elutriation-methods, sieving, and wind-sorting. The chapter is profusely illustrated, and most of the apparatus described is figured.

The third chapter concerns the practice of mechanical analysis, with a critical discussion of preparing samples for analysis. In addition to the boiling of the samples, dispersion by shaking and by dialysis are treated at some length. Gessner recommends dialysis when samples contain electrolytes which tend to flocculate the suspensions. A chart is furnished, displaying in flow-sheet fashion the steps involved in securing proper suspensions for the final analysis. The author also discusses the choice of methods available for particular types of material, and describes graphic means of displaying the data secured. An appendix, including tables of specific gravities, viscosities, etc., will prove of value for ready reference.

Workers who have a command of German will find the volume an indispensable aid to their work, and it deserves a place in the well-equipped laboratory of sedimentary petrology.

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NORTH, FREDERICK JOHN, Keeper of the Department of Geology in the National Museum of Wales, *Limestones.* London: Thomas Murby and Co., 1930. 467 pp., 236 figs. $4.00.

The title indicates a book of marked specialization but the reader is soon impressed by the diversified nature of the material considered in the treatment of the subject. The book might be described as a general reference written for the educated person not trained in geology. It contains sufficient explanatory material and definitions of terms used to serve as a textbook for an elementary course on the stratigraphy of British limestones.

Part One deals in three chapters with the nature, origin and varieties of limestones. In Chapter I twenty-three pages are devoted to a concise statement in simple language of the classification of rocks and the formation, consolidation, and deformation of sediments, with the emphasis placed on the calcareous rocks. The theory of isostasy is explained briefly without a mention of the word, and in another paragraph the theory of continental drift is accepted as a possible explanation of the Alpine mountain structure.

Chapter II is a twenty-six page discussion of the properties and varieties of limestone that is worthy of reading by any student of sediments. The author considers dolomite as a separate type of rock from limestone but recognizes a close similarity in origin, structure, and in the uses of the material. The occurrence and origin of limestone is discussed and especial emphasis is placed on the part played by organisms in the building of such rocks. This is the conventional idea which has become orthodox to the extent that few students recognize the large volume of material which comprises the matrix of many beds of limestone that contain few fossil remains. It is true that coquina limestones are common throughout the geologic column but they make a comparatively small percentage of the total. The discussion of limestones of mechanical origin is better than usually found in books of such a general character. Limestones made from pre-existing limestones are described and it is inferred that most of the fine-grained, compact "china-stone" limestones are of detrital origin. Numerous examples of dunes of calcareous material are cited and the conditions for formation and preservation of such deposits are discussed. A comparison with the formation of loess is suggested. In a footnote describing loess the common European and Asiatic localities are named and the author states "similar material occurring in North America is known as *adobe*." No mention is made of the well-known extensive deposits of loess in the central part of the United States. Several pages are given to the discussion of dolomites.

Chapter III gives the geologic distribution of limestones with a general and elementary explanation of the geologic column and geologic maps.

Part II containing Chapters IV to XII is a discussion of the distribution of limestones in Great Britain arranged by geologic systems. Each chapter deals with one or two systems; the stratigraphic divisions are explained, the important beds are named, the geographic distribution is stated, and the physical and biological characteristics of the limestones are discussed. A generalized map showing the geography of Great Britain during the period discussed is included in each chapter. Throughout this part of the book, which includes almost 250 pages, the discussion is personified by illustrations and comments of the many men who have contributed to the study of the geology of Great Britain. The frequent use of fossil and stratigraphic scientific names might be distracting to the average lay reader.

Part III, containing Chapters XIII to XVIII, deals with limestone in relation to scenery, agriculture, water supply, and industry and is full of interesting facts and examples of the large part played by limestones in the life of most individuals. Especially good are the discussions of water supply and the distribution of ore bodies in limestone.

The Appendices include a general classification of the animal kingdom, analyses of limestones, production data for Great Britain, physical properties of limestones, and additional notes.

Following each chapter there is a bibliography of pertinent articles. The entire book is well illustrated, in fact, this is a major attraction of the book. The book contains much of value to the geologist interested in limestone and in the general stratigraphy of Great Britain.

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April 1, 1932

WENTWORTH, CHESTER K., *The Mechanical Composition of Sediments in Graphic Form*. University of Iowa Studies in Natural History, Vol. XIV, No. 3, n.s. No. 219, 1932. 127 pp., 59 pls. 75 cents.

The title of the paper tells exactly what is to be found in it. Various causes have delayed the publication of the material more than five years. An explanation of the work and the source of the

data are given in four pages, followed by 828 mechanical analysis diagrams on 59 plates. The graphs are arranged according to environment of deposition and for the most part represent sediments in the process of accumulation; a few more than a hundred analyses are of ancient sediments.

The analyses have been compiled from a number of published and unpublished sources and converted to the uniform geometric ratio scale of 1-2-4-8 etc., mm. It is hoped that this publication will encourage further analytical work along the same line and especially the general acceptance of the 1-2-4-8, etc., mm. scale. It is distracting, in addition to being inconvenient, to try to compare analyses on different grade scales. Wentworth has published several articles explaining the scale used. He admits that it is not perfect, but the reviewer believes that it is as satisfactory as any of the numerous grade scales intermittently used by various workers.

Wentworth's paper is a notable contribution and will be much used as a reference but it should be used with a marked degree of caution. The current status of our knowledge of sediments does not permit the interpretations that are often made of ancient sediments by comparison of their size-grade distribution with that of modern sediments.

The experience of the reviewer in the handling and comparing of mechanical analyses of sediments shows there are many factors to be considered; under the proper conditions there are duplications of results by different agents of deposition. With proper control of a stated set of conditions, such as the nature of the source material, the competency of the agent to transport, the length or period of transportation and effect of contaminating or modifying agents, a type of size-grade distribution may be determined. If any one of these factors is modified, however, the result will be changed, a new size-grade distribution graph will result which may be similar or so nearly the same that it can be readily confused with another sediment of entirely different origin. For these reasons the comments which follow are offered by the reviewer.

Many examples of similarities of graphs in the various genetic classes used in this booklet may be cited. Eolian, fluvial, and marine sands should show distinct differences but a comparison of the figures listed under "Eolian" with the figure listed for one or both the other types of sand will show some striking similarities.

Eolian Sands *Figure No.*	*Fluvial Sands* *Figure No.*	*Marine Sands* *Figure No.*
29	322, 390	599
35	494	
41		624
49		615
58	396	600
65	327	
76	271	691
	366, 377	750

A careful study of the graphs cited above will show some differences in a few cases. How significant are these differences? Under certain conditions very slight differences, hardly apparent in some graphs, may mean more than some of the more obvious variations. The shift of the major grade to a position one grade coarser or finer may mean only that the competency of the agent is stronger or weaker or that the source material is different but may have no significance in proving the agent or site of deposition. A shift of the principal subsidiary grade from the coarse to the fine side of the major grade, or the reverse, may mean very little; a study of the graphs of the same agent will show numerous changes of this type.

One of the major objections to the use of size-grade distribution graphs for comparative purposes involves the method of sampling the sediment. In some types of sampling there are limiting factors which are difficult to overcome. In taking samples from outcrops, river bars,

ocean and lake beaches, it is possible to control the sample and to get material that will be representative of a single set of conditions. For example, a sample taken from a forest lamina will represent a single condition of current competency whereas a sample taken to include several such zones may show a wide variation of sizes due to the different capacities of transport. The mechanical analysis in the latter case will show a wide size-grade range and may show secondary maxima but the analysis of the first sample will show marked sorting or restricted size range. In the same way sampling of beach deposits shows wide variations for the numerous zones of sediment and possible combinations of composite samples. Any random sampling or the taking of composite samples will result in mechanical analyses of very general character which because of the mixture of deposits made by any variation of conditions tends to mask the possible diagnostic features of the particular agent or environment.

Future workers on the mechanical composition of sediments should keep in mind the need for improvement of methods of sampling and in their descriptions state the exact value of the zones sampled. There is much to be learned from mechanical analyses but the variables have not been satisfactorily evaluated.

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DISCUSSION

SUGGESTION REGARDING THE ORIGIN OF ROCK BOTTOM AREAS IN MASSACHUSETTS BAY

Trowbridge and Shepard,[1] in their article "*Sedimentation in Massachusetts* Bay," describe the sediments of the Bay as *generally occurring in belts roughly* parallel to the coast;

> . . . sand and gravel occur in the shallow zones near the coast, while in the deeper water, clay and silt form a larger portion of the deposits. One of the features not clearly understood is the zone of rock bottom which separates the coastal fringe of sand and the outer zone of sand and gravel.[2]

There are considerable areas of rock bottom indicated on the Massachusetts Bay chart, but because of the water depth, 50 to 100 feet, the sampling apparatus was not competent to tell whether these contain ledge rock or large rock fragments. The authors offer two explanations of the absence of fine sediment in such locations; (1) that the glaciers scraped off the sediments from these areas and waves and currents have been powerful enough to prevent later covering, and (2) that the sediment might have been washed off by the waves when the sea was lowered by the locking up of ice in the continental glaciers.

I believe it is very possible that most of the "rock bottom" areas of Massachusetts Bay contain boulders of glacial origin, left as a lag concentrate on a glacial till bottom. In an early stage of my study of the bottom of Lake Michigan, in the vicinity of Chicago, I found such deposits apparently forming a belt whose inshore margin lies approximately a half-mile from shore. During the first investigation, made near Grosse Point, fourteen miles north of Chicago Harbor, a drag-bucket sampling device was used. Samples of sand were obtained from within a half-mile of shore, but beyond this limit a clanking noise often was audible as the sampler was dragged over the bottom in depths of from 22 to 35 feet. *In such cases it would be brought to the* surface with its cup empty, but with faint streaks of clay adhering to the outside walls. The few meager samples obtained from this zone consisted of small pebbles or of a fine plastic clay. The conclusion that the bottom is made up of glacial till covered by a layer of pebbles was substantiated by a second suite of samples taken offshore from Jackson Park, seven miles south of Chicago Harbor. The drag-bucket yielded results similar to those obtained at Grosse Point, but an Ekman sampler, patterned after one loaned me by Dr. P. D. Trask, was used where the drag-bucket failed to secure sediment, and in some cases it brought up vertical core samples of glacial till with a layer of pebbles at the top of the column.

These data have been interpreted as indications of a glacial till bottom which is being subjected to wave erosion, so that the finer constituents are removed and the coarser are left as a lag deposit. The typical wave action adjacent to the bottom, consisting of a quick shoreward oscillation and a slower but longer continued seaward one, would move sand particles toward the beach and clay particles toward deeper water. The resultant zoning of deposits would produce a sequence of sand, gravel, and silt and clay in a direction perpendicular to the shore. The occurrence of a till bottom is not unknown in more ancient lake basins. That portion of the bottom of post-glacial Lake Chicago which is exposed in the Chicago Region is mainly a till plain, bordered by beach deposits and other shoreline phenomena.[3] A considerable

[1] *This Journal*, vol. 2, pp. 3-37, 1932.
[2] *Idem.*, p. 6.
[3] Provisional Geological Map of the Chicago Area, by J. Harlan Bretz, Illinois Geological Survey.

part of the basin of post-glacial Lake Agassiz is covered by wave-altered till, as is shown by Map 254A, Geological Survey of Canada, (Winnipeg Sheet, Surface Deposits) by W. A. Johnston.

The depths of the rock bottom areas of Massachusetts Bay are somewhat greater than those represented in the above-mentioned areas, but the more violent wave action of the Atlantic Coast could be expected to erode a till bottom in depths of 100 feet or more. Kindle[4] gives some striking illustrations of the effects of wave action in deep water, the most conclusive of which is the destruction of the tug *Walker*. The vessel was sunk in 65 feet of water near Nicholson's Island in Lake Ontario, with 75 tons of coal on board. During the eleven years that it lay on the bottom, its hull was smashed and all of the coal was removed.

[4] Kindle, E. M., *Trans. of the Royal Society of Canada*, vol. XIX, Third Series, pp. 29-30, 1925.

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May 23, 1932